FACIES ANALYSIS AND SEDIMENTATION OF BHANDER SANDSTONE OF VINDHYAN SUPERGROUP IN PARTS OF UTTAR PRADESH – RAJASTHAN STATES, INDIA

ABSTRACT

OF THE THESIS SUBMITTED FOR THE AWARD OF THE DEGREE OF

Doctor of Philosophy

IN

GEOLOGY

By

AABIROO MAJID

Under the Supervision of

Dr. A.H.M. Ahmad

DEPARTMENT OF GEOLOGY
ALIGARH MUSLIM UNIVERSITY
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ABSTRACT

The Upper Bhander Sandstone of Vindhyan Supergroup is well – exposed in and around Agra-Fatehpur Sikri region of Uttar Pradesh and adjoining parts of Rajasthan. It represents the southwestern part of the Great Vindhyan Basin. The present study aims to reconstruct the provenance, tectonic setting and depositional environment of the Upper Bhander Sandstone through its detailed fieldwork and petrographic study. Thirteen well exposed lithosections were measured from different localities of the Upper Bhander Sandstone.Lithosections were prepared on the basis of field data and lithofacies were identified. Petrographic study includes analysis of texture, detrital mineralogy and diagenesis.

The textural attributes including size, sorting, skewness, kurtosis, roundness, sphericity and their interrelationship and textural maturity of the sandstones were studied with a view to interpret the provenance and estimating the influence of texture on detrital modes and petrofacies. The sandstones are generally fine to medium grained, moderately sorted to moderately well sorted, strongly fine skewed and mesokurtic to leptokurtic. The detrital grains are generally sub-angular to sub-rounded and of medium sphericity. Texturally the sandstones are in general mature to supermature and show bimodality. The interrelationship between various textural parameters appear to be normal, thereby, suggesting that the original texture of the sediments and by implication, original detrital modes are largely preserved and have not been affected by diagenetic process.

The sandstones are compositionally supermature with very high amount of quartz (average 96%) followed by feldspar, mica and rock fragments. The detrital mineralogy suggests that they were derived from a variety of source rocks (mixed provenance). Sediments liberated from their source probably have undergone transportation for a distance of few hundred kilometers. The presence of small

amount of feldspar and rock fragments may be due to the transportation of sediments by high gradient streams and rapid destruction of feldspar by abrasion.

The mineralogical maturity of heavy mineral assemblages of source rocks is defined by Zircon-Tourmaline-Rutile index (Z-T-R). The high percentage of Z-T-R index value (79.16) with low percentage of rock fragments and feldspar in the studied sandstone indicates prolonged abrasion or high intensity of weathering in the source area.

Lithofacies analysis of the Upper Bhander Sandstone was carried out in order to interpret the palaeocurrent direction and their depositional environment. Palaeocurrent data indicate a dominance of shoreward migrating megaripples and wave ripple crests oriented approximately parallel to the paleo-shoreline with a distinct longshore component. The present study indicates that sandstones were formed under varying hydrodynamic conditions of island barrier complex system represented by tidal-inlet, inter-tidal flat and backshore-foreshore conditions.

The data on the types of quartz are plotted on the provenance discrimination diagram of Basu et al., (1975), in which the data plots in the plutonic and middle to high rank metamorphic fields with almost equal contribution from each component indicating a source area containing largely of plutonic and upper metamorphic rocks, which represent the exposed roots of magmatic cores or older crystalline basement in the area.

The plots of the Upper Bhander Sandstone on Qt-F-L and Qm-F-Lt diagrams suggest that the detritus of the sandstones were derived from the granite-gneisses exhumed in the craton interior and medium to high grade metamorphic supracrustals forming recycled orogen provenance. The sediments were deposited in intracratonic rift basin conditions as evidenced from Qp-Lv-Ls diagrams. The Qm-p-K plot of the data shows that all the sediment contribution is from the continental block basement uplift provenance and is reflected in mineralogical maturity of the *sediments. Dominance of quartzarenite and good textural maturity of sandstones suggest that the highlands formed by uplifted fold belts provided sediment debris to low relief area through their protracted erosion.*

The sandstones are cemented with silica and iron-oxide cement which are clearly distinguishable from detrital components and the former have not modified the later except in some patches. The abundance of long and point contacts in the studied sandstones indicate that the sandstones were not subjected to large pressure solution, as a result of either shallow burial or early cementation. Presence of sutured boundaries of quartz overgrowth indicates the post cement compaction. The high contact index value (2.16) due to dominance of point and long contacts is attributed to mechanical compaction.Diagenetic processes such as dissolution, replacement etc., have brought about little modification of the original detrital constituents.

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Dedicated
to
My Parents

Dr. A.H.M. Ahmad
M Sc., Ph.D.
Reader

DEPARTMENT OF GEOLOGY
ALIGARH MUSLIM UNIVERSITY
ALIGARH -202002, INDIA
Phones : Off. : 091 (571) 2700615
Mob. : 9411465116
Res. : 091 (571) 2703827
Fax : 0571-2700528
E-mail : ahmahmad2004@yahoo.com

Dated : 18.08.2009

Certificate

Miss Aabiroo Majid carried out her research on, "Facies Analysis And Sedimentation of Bhander Sandstone of Vindhyan Supergroup in Parts of Uttar Pradesh- Rajasthan States, India" under my supervision at the Department of Geology, Aligarh Muslim University, Aligarh.

I certify that the research work is an original contribution of the candidate and is allowed to submit the thesis for the award of the Doctor of Philosophy of Science in Geology, Aligarh Muslim University, Aligarh.

a. m. ahmad

Dr.A.H.M. Ahmad

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Aabiroo Majid

Aabiroo Majid

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CHAPTER I

INTRODUCTION

The Proterozoic Era of the earth's history was a period of accelerated crustal growth (Taylor and McLennan, 1985) during which mobile belts, sedimentary basins and the first stable cratons developed (Windley, 1984). The Proterozoic Era represents the period of the earth's history that began 2.5 billion years ago and ended at ~ 542 million years ago. Abundant microscopic life, mostly bacteria and cyanobacteria flourished during this time. The first evidence of oxygen buildup in the atmosphere came with the beginning of Mesoproterozoic Era. This global catastrophe brought extinction of many bacterial groups, but made possible explosion of many. A large part of the Peninsular Indian shield is occupied by Mid-Late Proterozoic platform covers. These vast sedimentary provinces (Figure 1) designated as the Puranas are the (1) Vindhyan Basin (2) Cuddapah- Kurnool Basin (3) Bhima Basin (4) Kaladgi Basin (5) Pranhita-Godavari Valley Basin (6) Chhattisgarh Basin (7) Indravati Basin (8) Khariar Basin (9) Abujhmar Basin (10) Bijawar Basin (11) Gwalior Basin and (12) Sukma or Sabari Basin. Although, in terms of their preservation geometry they appear to be discrete basins, it is hard to say whether, they represent separate basins or multiple depocentre within a large depositional area of sub-continental dimensions (Chakraborty, 2006).

Amongst the aforementioned basins, the Vindhyan basin, situated in the central part of India is one of the largest Meso-Neoproterozoic basins of the Indian Peninsula. It is arcuate in shape with large expanse of shallow marine sedimentary rocks of calcareous, argillaceous and arenaceous sediments.

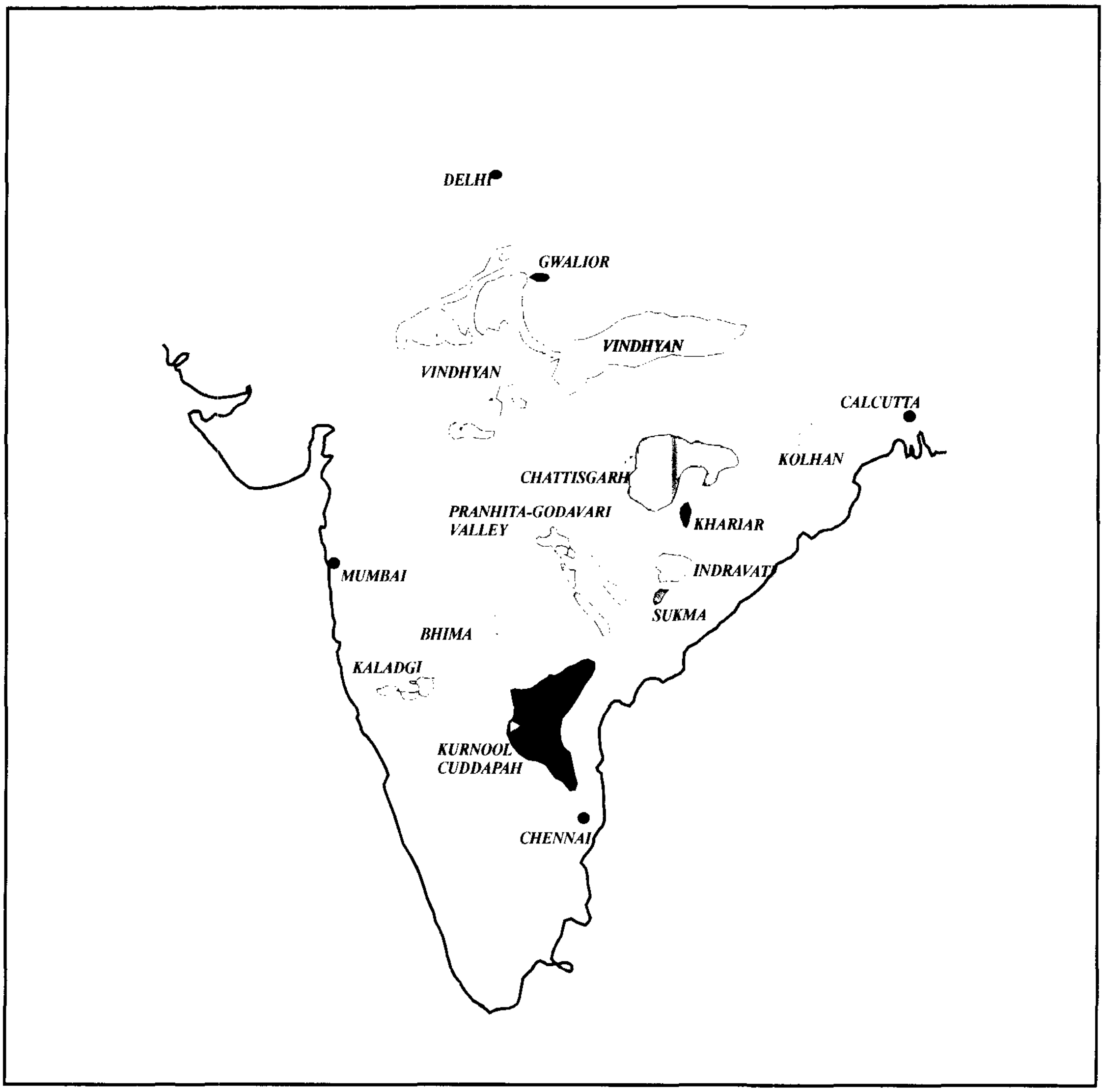


Figure 1. The Mid-Late Proterozoic Sedimentary Basins of Peninsular Indian Sheild.

It covers an area of about 1,62,000km^2. The Vindhyan basin is bordered by the Aravalli-Delhi orogenic belt (2500-900Ma) (Roy, 1988) in the west, Son-Narmada lineament in the southwest and the Satpura orogenic belt (1600-850Ma) (Verma, 1991) in the southeast. The Bundelkhand Massif occupies the north-central part and is fringed by Paleoproterozoic Bijawar rocks along the eastern edge and their equivalent Gwalior rocks. The basin shows geometry of a half graben (Ram et al., 1996) and is deepest towards the southwest in the proximity of Son-Narmada lineament. It gradually shallows up to the northwest towards Bundelkhand Massif. The northern extension of the basin in the Ganga Valley beneath the Gangetic alluvium is postulated based on geophysical and drilling data of Oil and Natural Gas Corporation of India. However, recently, the absence of Vindhyan sediments in the subsurface sequence of Ganga Valley has been reported based on acritarch studies (Prasad et al., 2005).

Although the rocks of Vindhyan Supergroup are generally flat resting unconformably over the Bundelkhand Granite at the northern margin of the basin, the southern and western margins of this sickle-shaped basin are folded and faulted showing tectonic contact with Pre-Vindhyan basement (Srivastava and Sahay, 2003). This basin is limited within two major faults, i.e., the Great Boundary Fault marking the northwestern margin and Central Indian Suture demarcating the southeastern margin. The maximum stratigraphic thickness of sedimentary fill exceeds about 4500m (Gokaran et al., 1995). The rocks, except near margins of the basin are predominantly undeformed, unmetamorphosed successions of sandstones, shales, carbonates, minor conglomerates and mafic volcanic products. The basin is spread over the states of Rajasthan, Madhya Pradesh, Uttar Pradesh and Bihar and divided into two sub–basins - Chambal Valley in the west and Son valley in the east. In the Chambal Valley, thick Neoproterozoic sediments corresponding to Rewa and Bhander groups of Vindhyan Supergroup are present and expose mainly calcareous and argillaceous facies in the northern part with rich algal mats (stromatolites). However, the southern part of Chambal Valley is covered by the Deccan Traps. The geological investigation and studies in the Vindhyan basin were initiated from the mid 19th century. It attracted the attention of explorationists because of its large expanse of shallow marine sedimentary rocks and huge thickness. The Son Valley sector strikes ENE-WSW and its depositional axis runs close to Son-Narmada Lineament and swerves to the northwest in the Chambal Valley sector. Recently this basin has been taken up for oil and gas exploration and a wealth of subsurface information are available through bore hole logs (Sinha et al., 2002).

The lithological assemblage of the Vindhyan Supergroup is further divided into Semri, Kaimur, Rewa and Bhander groups (Table 1). Taking into account litho component variants, Bhander, Rewa, Kaimur and Semri are the type areas of these consanguineous litho components.

Table 1. Generalized Lithostratigraphy of Vindhyan Supergroup

Group	(After Krishnan, 1982)	(After Bose et al., 2001)	
Bhander	**Upper Bhander Sandstone** Sirbu Shale Lower Bhander Sandstone Lower Bhander Limestone	**Upper Bhander Sandstone** Sirbu Shale Lower Bhander Sandstone Bhander Limestone Ganurgarh Shale	
Rewa	Upper Rewa Sandstone Jhiri Shale Lower Rewa Sandstone Panna Shale	Rewa Sandstone Rewa Shale	
Kaimur	Dhandraul Quartzite Scarp Sandstone & Conglomerate Bijaigarh Shale Upper Quartzite Silicified Shale /Susnai Breccia Lower Quartzite	Upper Kaimur Sandstone Bijaigarh Shale Lower Kaimur Sandstone	
Semri		Lower Vindhyan Semri Group	
		Formation	Member
	Rohtas Limestone Glauconite Bed Fawn Limestone Olive Shale Porcellanite Kajrahat Limestone Basal Conglomerate	Rohtas Kheinjua Porcellanite Kajrahat Basement rocks Deoland	Rohtas Limestone Rampur Shale Chorhat Sandstone Koldaha Shale Porcellanite Kajrahat Limestone Arangi Shale Bundelkhand Granite

Vindhyan sediments are considered to have deposited in environments ranging from fluvial to deep marine (Bhattacharya and Morad, 1993; Bose and Chakraborty, 1994; Chakraborty, 1993; Chakraborty and Bhattacharya, 1996). According to Chanda and Bhattacharya (1982), the Vindhyan basin developed in an intracratonic embayment with conditions fluctuating from beach environment through tidal flat lagoon complex to tidal shelf along with barrier beach – dune complexes. Storm dominated sedimentation has been reported by Bose et al., (1988) and Chaudhari et al., (1999). Bose et al., (2001) suggested that Vindhyan sedimentary rocks are mostly marine possibly deposited in an E-W elongated Epeiric Sea opening westward.

Singh (1973) interpreted the depositional environment of the Vindhyan Basin which includes high gradient rivers to a complex interrelated with shallow marine environment. Srivastava and Sahay, (2003) suggested that the Vindhyan sediments were deposited by means of tidal and turbidity currents operating side by side near the continental platform region to give rise to quiet (stable) and agitated (unstable) depositional cycles. Gupta et al., (2003) postulated that the Vindhyan sediments were deposited under recurrent fluctuating sea level conditions. Sarkar et al., (2006) suggested that the deposition of Chorhat Sandstone of Semri Group ranges from shallow shelf to coastal margin with aeolian sand-sheets. Banerjee and Jeevankumar (2007), have suggested that the Rohtas Limestone of Semri Group was deposited in shallow agitated shelf environment. Sarkar et al., (2008) suggested that Sonia Sandstone of Bhander Group was laid down over a wider range of coastal environment, from the upper neritic transition to the supralittoral zone, shallow sublittoral- littoral-supralittoral transition.

GEOLOGICAL SETTING

The 4500m thick Vindhyan Supergroup is subdivided in two successions on the basis of their distinct tectonic settings. The Lower Vindhyan developed in an intracratonic rift basin (Bose et al., 1997), the Upper Vindhyan formed in an intracratonic sag basin (Sarkar et al., 2002) with a compressional interlude in between. The Upper Vindhyan comprises three formations, the Kaimur, Rewa and Bhander in ascending order. The formations underlying the Bhander Group are entirely siliciclastic and inferred as fluvio-marine-eolian products (Bose and Chakraborty, 1994; Chakraborty, 1995; Bose et al., 2001). Their constituent beds are sub-horizontal and show evidence of mild deformation. The Bhander Formation comprises five members, the Ganurgarh shale, Bhander Limestone, Lower Bhander Sandstone, Sirbu Shale and Upper Bhander Sandstone, from the base upwards; these units succeed fluvio-eolian deposits of the underlying Rewa Formation (Bose and Chakraborty, 1994; Chakraborty, 1995) and maximum flooding is recorded above the base of the Sirbu Shale (Sarkar et al., 2002; Bose et al., 2001). An extensive carbonate sea developed at an early phase of the transgression (Ray et al., 2002). The Upper Bhander Sandstone is the topmost unit of the Bhander Group of the Vindhyan Supergroup and is well exposed, along with the younger members of the Bhander Group in the central India (Sarkar et al., 2004). The Upper Bhander Sandstone is, however, mainly terrestrial and of overall progradational affinity.

CHOICE AND LOCATION OF INVESTIGATED AREA

The huge crystalline massif (Bundelkhand Granite) located in the northern part of the central sector of the Vindhyan Basin divides it into two blocks, a western and an eastern one. The rather inaccessible western block has received far less attention of the workers than the eastern one. In view of this the Upper Bhander Sandstone formation of Bhander Group has been chosen in this study which may help to partly unravel geological riddles about western block. Furthermore, the Upper Bhander Sandstone occurring in the form of parallel ridges is the only exposed formation along Agra-Fatehpur Sikri tract and thus provides excellent opportunity to study the sedimentary attributes of the formation of Vindhyan Supergroup in this region (Figure 2).

The investigation area is spread over 70 Square kilometers and is delimited by latitude 26°50′ and 26°56′ 30″ N and longitude 77° 25′ and 77° 37′ E within the Survey of India topographical sheets number 54F/5 and 54 F/9 and forms the northerly extension of great Vindhyan Basin. The area lies in the south-west of Agra-Fatehpur Sikri tract and represents small part of long belt of the Upper Bhander Sandstone Formation which extends for about >100km up to Karauli. The studied area has a dry climate with hot summers and cold winters intervened by a short monsoon season. Average rainfall is 657.8mm. The land of this region is generally fertile and flat. The general strike of the area is approximately NE-SW. The amount of dip ranges between 3° to 35°.

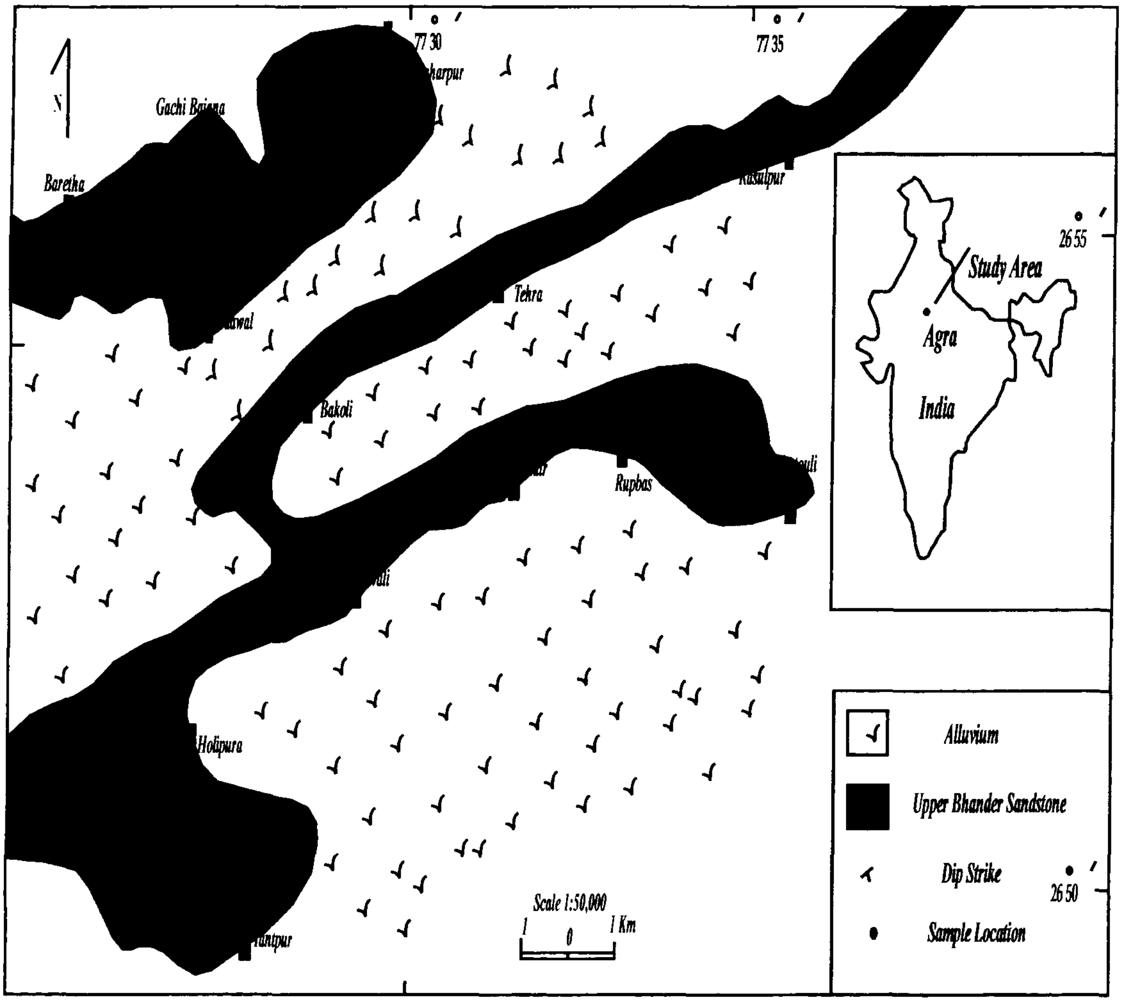


Figure 2. Geological map of the study area in parts of Uttar Pradesh-Rajasthan States.

PREVIOUS WORK

The European geographers who studied the area applied the name Vindhyan to the scarp "range" along the northern side of the Narmada Valley. In 1854, the Vindhyan Group of rocks attracted the attention of Geological Survey of India and Oldham (1859) used this name to designate the great sandstone formation of Bundelkhand and Malwa capitals. He also studied these rocks in Central India and proposed the name Vindhyan for the whole gamut of formations and classified them into three sub groups viz., Kaimur, Rewa and Bundair in ascending order.

Medlicott (1859) surveyed the region north of Narmada Valley including Bundelkhand area and upheld Oldham's classification. Mallet (1869) made a regional study of the Vindhyan rocks in northwestern and central part of the Vindhyan range. He retained the earlier classification but concluded that the "sub-Kymore" series of the Son-Valley and Semri series of Bundelkhand were one and the same. He subdivided the Vindhyans into Upper and Lower. The Kaimur and Rewa were placed in Upper Vindhyan, the Semri and Sub- Kaimur series in Lower Vindhyan. Later Hacket (1881), studied the present area, in the central and eastern Aravalli region. He described that the area lies on the long line of hills forming the northern edge of the Vindhyan plateau and extends from Fatehpur Sikri to southwestern direction through Rimtumbour near Chittorgarh. Coulson (1927) mapped the Bundi state in Rajasthan and studied the Upper Vindhyan rocks in detail. Fox (1928) tried to solve the dispute of boundary between Upper and Lower Vindhyan. The break in sedimentation is proved by the presence of Sushi breccia and Porcellanite which are proved to be most suitable horizons for placing the boundary between Upper and Lower Vindhyan. But Fox (1928) was unable to find this breccia insitu.

Auden (1933) surveyed the Vindhyan rocks in Son Valley (Mirzapur) originally surveyed by Mallet (1869) and later on by Vredenburg and Dutta (1901). Vredenburg and Dutta (1901) divided the system into four more or less equipartite series. the Semri, Kaimur, Rewa, and Bhander in ascending order. They discarded the term Lower and Upper Vindhyan.

Heron (1936) carried out detailed mapping of the entire region describing the stratigraphic sequence, lithology and structural feature of the Vindhyan rocks. Ahmad (1962) reconstructed the paleogeography of the Vindhyan basin, after studying the geology of Vindhyan system. He mainly discussed the source of Vindhyan sediments which in his opinion owed their origin to Aravalli craton. He also gave an idea that Aravallis were almost peneplained at the time of Vindhyan sedimentation and the western Rajputana basin was connected with the main eastern basin. Large part of the Vindhyan basin went to form a craton during Gondwana period and a great thickness of Bhander and post- Bhander beds have been removed. Ahmad (1962) concluded that post-Vindhyan but pre-Gondwana rocks were deposited in this area.

Basumallick (1961) discussed sedimentological features of the Bhander Sandstone of Maihar, U.P. His studies were mainly based on directional elements; i.e., ripple marks, cross-stratifications and grain orientation noted in the Bhander Sandstone and suggested a tidal flat environment for this rock.

Jafar et al., (1966) on the basis of palaeocurrent studies suggest that the Vindhyan sedimentation took place in two phases, i.e., in a restricted basin in Semri times and in an extended basin across Aravalli craton.

Akhtar (1978) studied the paleogeography and sediment dispersal pattern of the Vindhyan basin. He mainly discussed the shoreline, palaeoslope and dispersal pattern of the Proterozoic sediments comprising the Bhander Group in Mandalgarh-Singoli area of southeastern Rajasthan and adjoining Madhya Pradesh. Earlier workers postulated a NW regional palaeoslope of the Vindhyan Basin on the assumption that the predominant palaeocurrent pattern reflected the palaeoslope. The study of Akhtar (1978) however, suggests that the predominant palaeocurrent pattern is independent of the palaeoslope and represents the longshore sediment dispersal. Singh (1980) worked on the depositional environment of Bijaigarh Shale in Son valley area of the Vindhyan Supergroup. His study revealed that the sediments were deposited in a transgressive phase which culminated in the development of extensive coastal sand deposits, overlying the Bijaigarh Shale.

Since then, number of workers have made significant contributions on various aspects of Vindhyan Supergroup of rocks including sedimentation history and age correlation, particularly in the eastern and central part of the Vindhyan Basin (Narian and Kaila,1982; Radhakrishna and Naqvi,1986; Das, 1988; Kaila et al .,1989; Yedekar et al., 1990; Verma,1991; Chakraborty and Battacharya,1996; VenkataChala et al., 1996; Banerjee, 1997; Sarkar et al. , 1998; Chakraborty et al .,1998 ; Bose et al., 1999,2001; Gupta et al., 2003;

Sarkar et al., 2004a; Sarangi et al., 2004; Banerjee and Kumar,2007; Prasad, B. 2007;Sarkar et al., 2008; Raza et al., 2009).

However very limited work has been done in southwestern part of the Vindhyan basin. A few authors such as Coulson (1927), Heron (1936), Nazish (1972), Prasad (1984) and Mathur (1985) made efforts in explaining the sedimentology, petrography and depositional environment of the youngest member of the Vindhyan basin outcropped in southwestern parts of the Uttar Pradesh and Rajasthan states. The present study is an attempt in this direction by taking up a detailed sedimentary analysis of the above mentioned area.

AIM AND SCOPE OF INVESTIGATION

The present study mainly aims at reconstructing the sedimentation history and facies analysis of the Upper Bhander Sandstone. An attempt is also made to study diagenetic aspect of the sandstone such as compaction, cementation and porosity reduction.

The field work was carried out during the month of December and January, 2006 and November, 2007. Thirteen well exposed lithostratigraphic sections were measured from different localities. Special attention was paid to study the nature of sedimentary structures like cross bedding, lamination, ripple marks etc. Lithosection were prepared on the basis of field data and litho facies were identified.

Thin sections prepared from 105 Sandstone samples were used for textural attributes such as size, roundness and sphericity to interpret the provenance and estimating the influence of texture on detrital mode and petrofacies. Bivariant plots were used to find out the interrelationship of various textural attributes. Cumulative frequency curves were plotted and statistical parameters of grain size were computed according to the method of Folk (1980). Thin section data on grain size was converted into sieve equivalents.

Detrital mineralogy of the sandstone including lighter and heavy mineral fraction were studied for the purpose of the petrographic classification of the sandstones and their provenance interpretation. The classification scheme of Folk (1980) based on composition of the detrital constituents and classification scheme of Dickinson (1985) emphasizing the tectonic setting of provenance were used for the studied sandstones.

Palaeocurrent data was employed to interpret the dispersal pattern of the sediments. For this purpose azimuthal data collected on large scale planar and trough cross bedding was used. Study of palaeocurrent included construction of palaeocurrent maps at different levels of sampling and determination of statistical parameters of azimuthal variability at each level.

Diagenesis is an important aspect of sedimentological investigation but published studies dealing with this aspect are scarce, especially those made on Vindhyan sediments in parts of Uttar Pradesh and Rajasthan. In the present study an attempt is made to study the diagenetic history of the sediments. The diagenetic aspects include compaction, porosity reduction and cementation. The study of diagenesis is based on examination of thin sections. Thin sections were employed to study types of grain contacts, porosity reduction and cement.

CHAPTER –II

LITHOSTRATIGRAPHY

The Upper Bhander Sandstone occurs in parallel ridges and shows frequent intercalations of shale. The shaly intercalations are common and occur by and large throughout the area under study. The Upper Bhander Sandstone is usually dark red in color with small white spots and pale pinkish passing into an almost white rock without red staining in some beds. The sandstone also shows white color along bedding plane and joints which is due to leaching of iron oxide cement by surface waters. Sandstone is hard and compact but at places soft and the thickness of the individual beds range between 3cm-1.5m.

Thirteen representative stratigraphic sections were measured and their vertical and lateral relationship was studied along with lithology and internal sedimentary structures. Vertical sections were measured at Rasulpur, Tehra, Bakoli, Rupbas, Ghatouli, Mewali, Jagnair, Holipura, Tantpur, Baretha, Gchadi Bajana, Bansi Paharpur village and Rudawal.The details of the measured section is as follows:

Rasulpur Village Section

A Lithostratigraphic section was measured at the village Rasulpur having thickness of about 17.1m (Figure 3) and is composed of sandstone and shale. The whole section shows pinching and swelling laterally just like different tidal channels occurring laterally. The thickness of the beds decreases laterally. The measured section has the following sequence:

Top

17.1-15.5 m	Yellow colored, medium grained, soft, laminated sandstone, lower contact is erosional and upper contact is not known, 1.6 m thick.
15.5-13.5 m	White colored, medium grained, soft, large scale tabular cross bedded sandstone, the bedding is slightly tangential, upper contact is undulating and lower contact is sharp, 2.0 m thick.
13.5-11.5 m	Pinkish white colored, medium grained, soft, symmetrical ripple bedded sandstone, sharp contact,2.0 m thick (Plate 1A).
11.5-10.5 m	Pinkish white colored, medium grained, soft, finely laminated sandstone and having small tabular cross-bedding, sharp contact, 1.0 m thick.
10.5-9.5 m	Pinkish white colored, medium grained, soft, low angle tabular cross-bedded sandstone with a channel body, sharp contact, 1.0 m thick.
9.5-8.5 m	Pinkish white colored, medium grained, soft, small scale asymmetrical ripple bedded sandstone, sharp contact,1.0 m thick (Plate 1B).
8.5-6.5 m	Pinkish white colored, medium grained, soft, finely laminated sandstone, opaque are arranged along the laminations, sharp contact,2.0 m thick.

6.5-6.0 m	Pinkish white colored, medium grained, soft, symmetrical ripple bedded sandstone, sharp contact,0.5 m thick.
6.0-5.5 m	White colored, medium grained, soft, deformed laminated sandstone, sharp contact,0.5m thick (Plate 1C).
5.5-5.0 m	Red colored, very fine grained, soft, straight contact, shale, 0.5m thick.
5.0-4.5 m	White colored, fine grained, hard and compact, massive sandstone, sharp contact, 0.5m thick.
4.5-4.0 m	Red colored, very fine grained, soft, straight contact, shale, 0.5m thick.
4.0-3.0 m	Pinkish white colored, fine grained, soft, small scale tabular cross-bedded sandstone, upper contact is sharp and lower contact is wavy, 1.0m thick.
3.0-2.5 m	Pinkish white colored, fine grained, soft, horizontal bedded thickly laminated sandstone, sharp contact, 0.5m thick.
2.5-1.5 m	White colored, fine grained, soft, small scale tabular cross-bedded sandstone, sharp contact, 0.5m thick.
1.5-0 m Bottom	Red colored, very fine grained, soft shale, straight contact, 0.4 m thick.

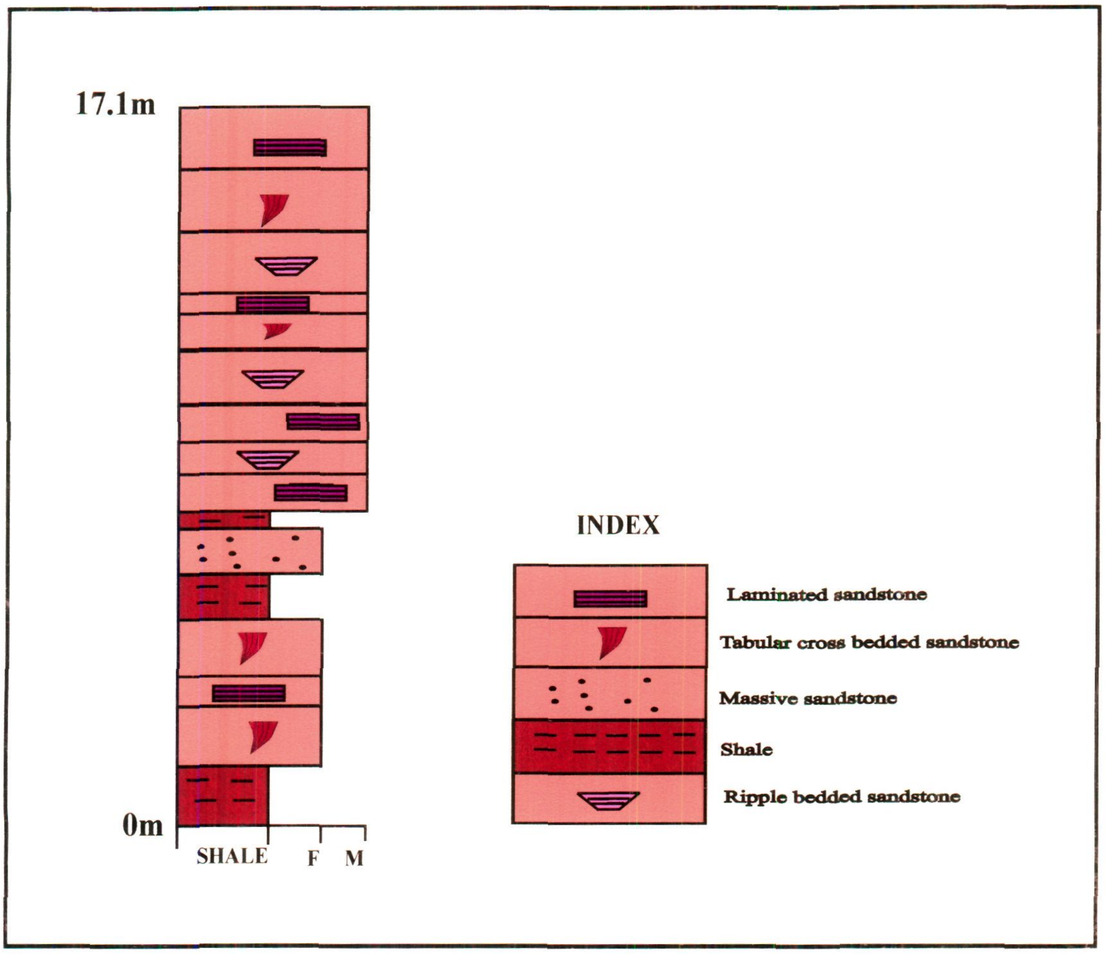


Figure 3 . Lithostratigraphic section measured near Rasulpur village.

PLATE I

A

B

C

PLATE I

A. Field photograph showing symmetrical ripple marks.

B. Field photograph showing asymmetrical ripple marks.

C. Field photograph showing laminated sandstone

Section Tehra Village

A Lithostratigraphic section was measured at the village Tehra, 24.6m thick (Figure 4) and is composed of sandstone and shale. The measured section has the following sequence:

Top

24.6-21.0 m	Reddish brown colored, medium grained, soft, tabular cross bedded sandstone, pinching and swelling common, lower contact undulating, 3.6m thick.
21.0-19.0 m	Red colored, medium grained, hard and compact, finely laminated sandstone, sharp contact, 3.0m thick.
19-17.5 m	Red colored, medium grained, hard and compact, thick bedded massive sandstone with round crested wavy ripples at the base, sharp contact, 1.5m thick.
17.5-17.0 m	Red colored, medium grained, soft, tabular cross-bedded sandstone, sharp contact,0.5m thick.
17.0-15.5 m	White colored, medium grained, soft, ripple cross bedded sandstone, ripples are asymmetrical and linguoid / lunate type, mud cracks and clay galls are present, sharp contact, 1.5 m thick.
15.5-15.0 m	Red colored, medium grained, soft, thick tabular cross bedded sandstone, sharp contact, 0.5m thick.

15.0-14.5m	Red colored, medium grained, soft, horizontal bedded, thickly laminated, sandstone, sharp contact, 0.5m thick.
14.5-13.0 m	Red colored, medium grained, soft, small scale tabular cross-bedded, laminated sandstone, sharp contact,3.0m thick.
13.0-11.5 m	Red colored, very fine grained, soft shale, straight contact, 1.5 m thick.
11.5-11.0 m	Red colored, fine grained, hard and compact, large scale trough cross-bedded sandstone, sharp contact, 0.5m thick.
11.0-10.5 m	Red colored, fine grained, soft, thick tabular cross bedded sandstone with presence of herringbone, sharp contact, 0.5m thick.
10.5-9.5 m	Red colored, very fine grained, soft shale, straight contact, 1.0 m thick.
9.5-8.0 m	Red colored, fine grained, hard and compact, small scale tabular cross-bedded sandstone, sharp contact, 1.5m thick.
8-7.5 m	Red colored, fine grained, soft, laminated sandstone, sharp contact, 0.5m thick.
7.5-7.0 m	Red colored, fine grained, hard and compact, tabular cross bedded sandstone with clay gals at base, sharp contact, 0.5 m thick.

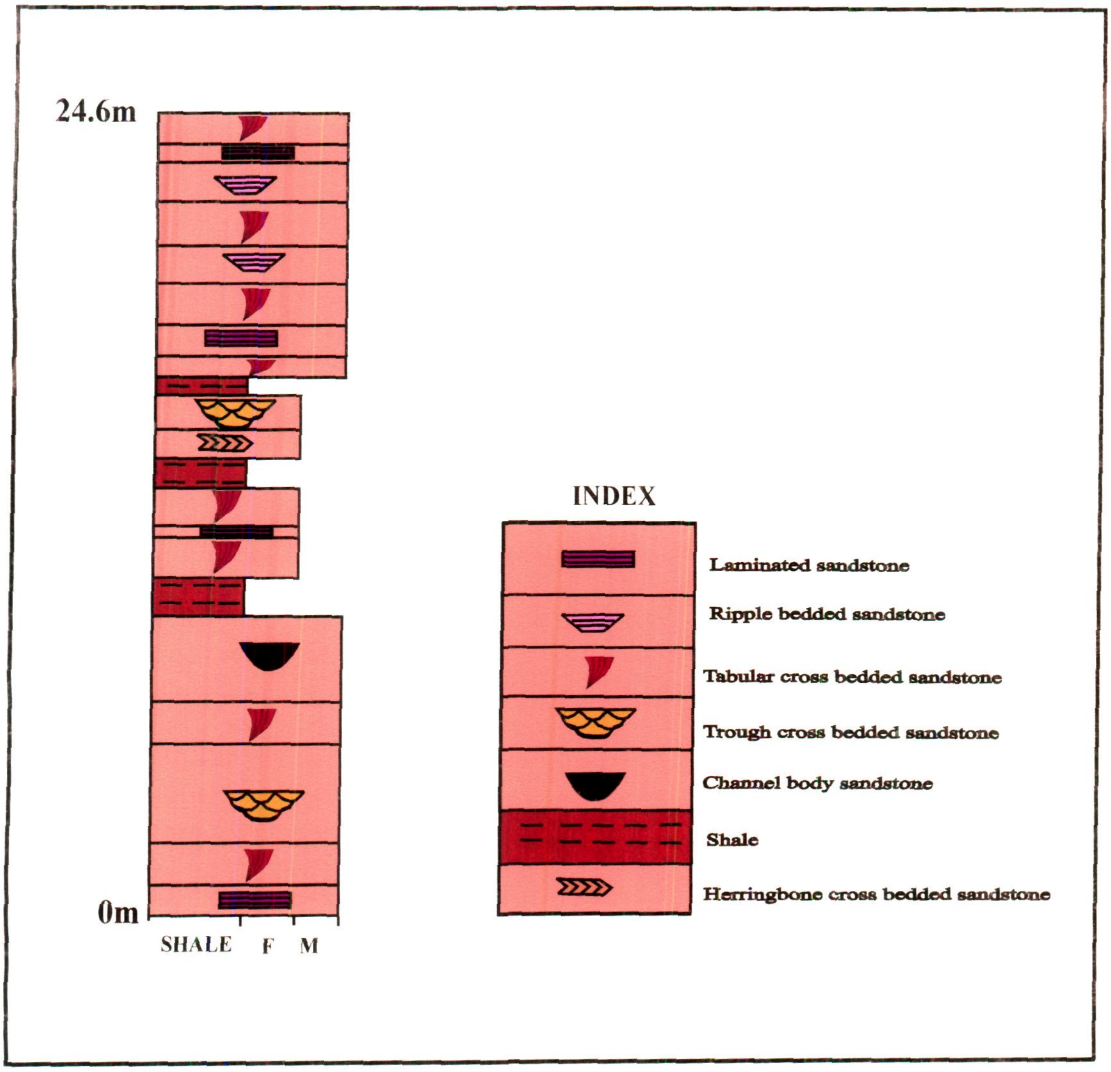


Figure 4 . Lithostratigraphic section measured near Tehra village.

7.0-6.0 m	Red colored, fine grained, soft sandstone with shale Intercalation, straight contact, 1.0 m thick
6.0-4.5 m	Red colored, medium grained, hard and compact, trough cross-bedded sandstone with clay gals at base, sharp contact, 2.0 m thick.
4.5-4.0 m	Red colored, medium grained, soft, tabular cross-bedded sandstone with channel body, sharp contact, 0.5m thick.
4.0-2.0 m	Red colored, medium grained, soft, trough cross bedded sandstone, sharp contact, 2.0m thick.
4.6-3.4 m	Red colored, medium grained, hard, massive sandstone with presence of clay galls, straight contact,1.2 m thick.
2.0-0.5 m	Red colored, medium grained, hard, massive sandstone occasional small scale tabular cross bedding, sharp contact, 0.5 m thick.
0.5-0 m	Red colored, medium grained, soft, laminated sandstone, sharp
<u>Bottom</u>	contact, 0.5m thick.

Bakoli Village Section

A Lithostratigraphic section was measured at the Bakoli village having thickness of about 16.5m (Figure 5) and is composed of sandstone and shale. The section measured has the following sequence:

Top

16.5-14.5 m	Pinkish white colored, medium grained, soft, symmetrical ripple bedded sandstone, sharp contact,2.0m thick.
14.5-12.5 m	Red colored, medium grained, soft, laminated sandstone, sharp contact, 2.0m thick.
12.5-11.0 m	Red colored, medium grained, soft, ripple cross bedded sandstone, clay galls are present, sharp contact, 1.5 m thick.
11.0-10.0 m	Red colored, medium grained, soft, laminated sandstone, sharp contact, 1.0m thick.
10.0-9.0 m	Pink colored, medium grained, soft, thick tabular cross bedded sandstone, upper contact is undulating and lower contact sharp, 1.0m thick.
9.0-8.0 m	Red colored, very fine grained shale, soft and having straight contact, 1.0m thick.
8.0-7.0 m	Red colored, fine grained, soft, trough cross-bedded, laminated sandstone, sharp contact, 1.0m thick.
7.0-4.0 m	Red colored, fine grained, soft, large scale tabular cross-bedded sandstone with lateral thinning of beds, sharp contact,3.0m thick.
4.0-2.0 m	Red colored, very fine grained shale, soft and having straight contact, 2.0m thick.
2.0-0 m	Red colored, medium grained, soft, small scale trough cross-bedded sandstone, sharp and straight contact, 2.0m thick.

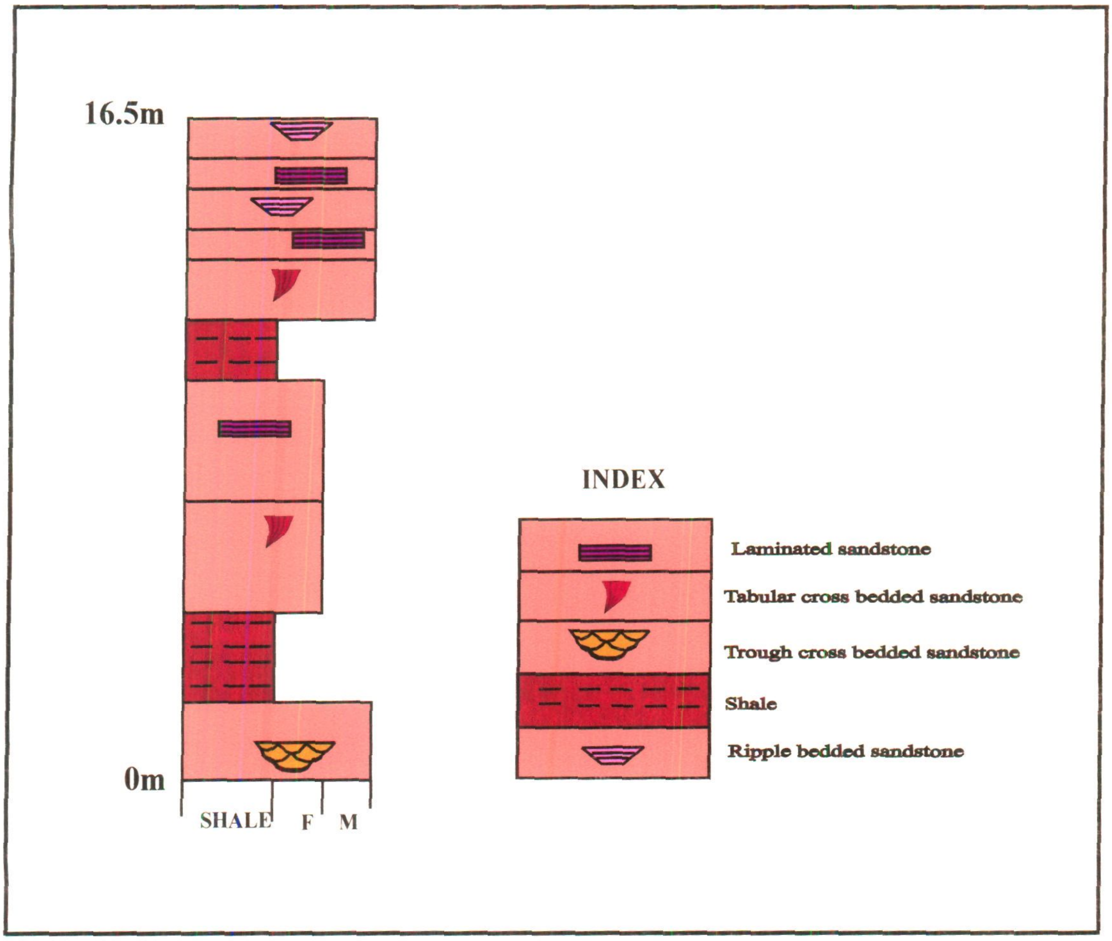


Figure 5 . Lithostratigraphic section measured near Bakoli village.

Rupbas Village Section

A Lithostratigraphic section was measured near Rupbas village is 6.8m thick (Figure 6) and is composed of sandstone. The measured section has the following sequence:

<u>Top</u>

6.8-6.0 m	Red colored, medium grained, soft, tabular cross-bedded with white colored large channel body having convex shape (due to erosion) flat bedded sandstone, sharp contact, 0.8m thick.
6.0-5.5 m	Pinkish white colored, medium grained, soft, large scale trough cross-bedded sandstone with lateral thinning of beds, sharp contact,0.5m thick (Plate IIA).
5.5-4.5 m	White colored, medium grained, soft, large scale tabular cross-bedded sandstone, thickly bedded and pinching and swelling common, sharp contact,1.0m thick(Plate IIB,C).
4.5-2.5 m	White spotted red colored, medium grained, small scale trough cross-bedded sandstone ,pinching and swelling of beds is common, sharp contact,2.0m thick.
2.5-1.0 m	Pinkish white colored, medium grained, soft, large scale tabular cross-bedded sandstone, sharp contacts,1.0m thick.
1.0-0 m	White spotted red colored, medium grained, hard, massive sandstone, beds nearly horizontal with parting lineation, hard, 1.0m thick.

<u>Bottom</u>

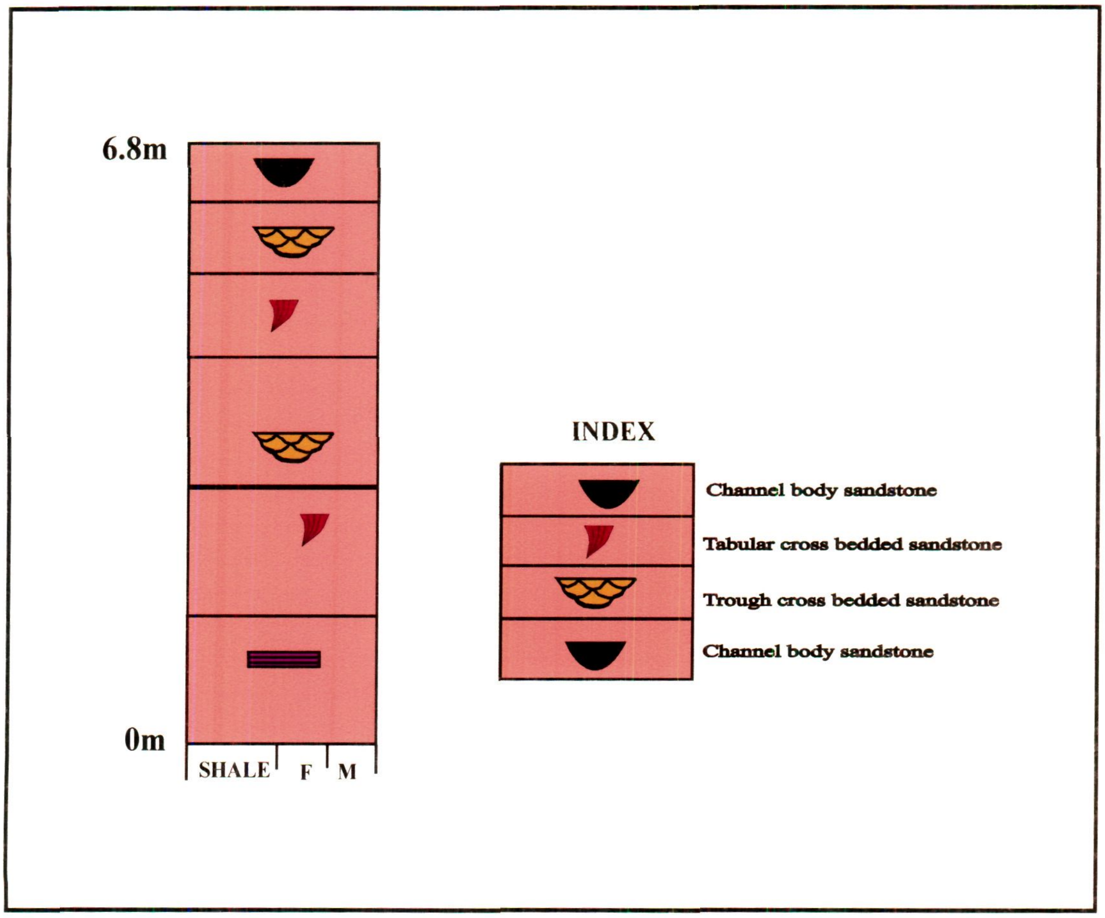
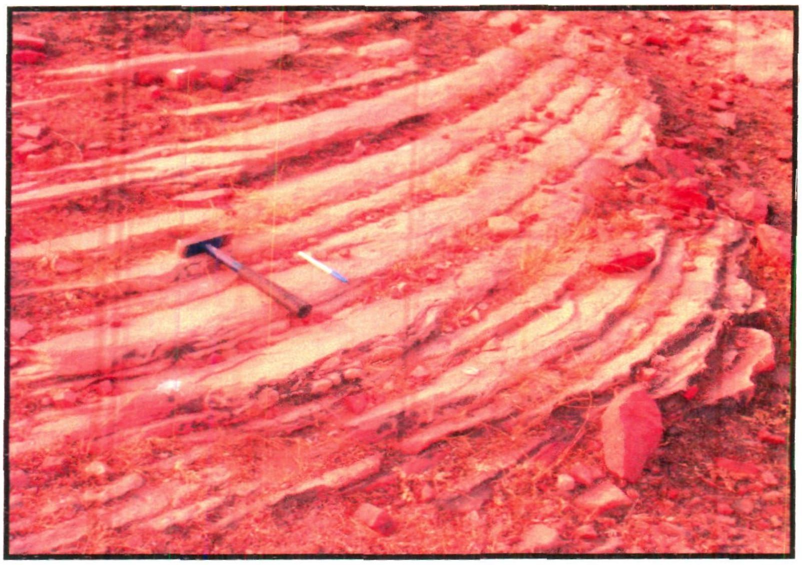


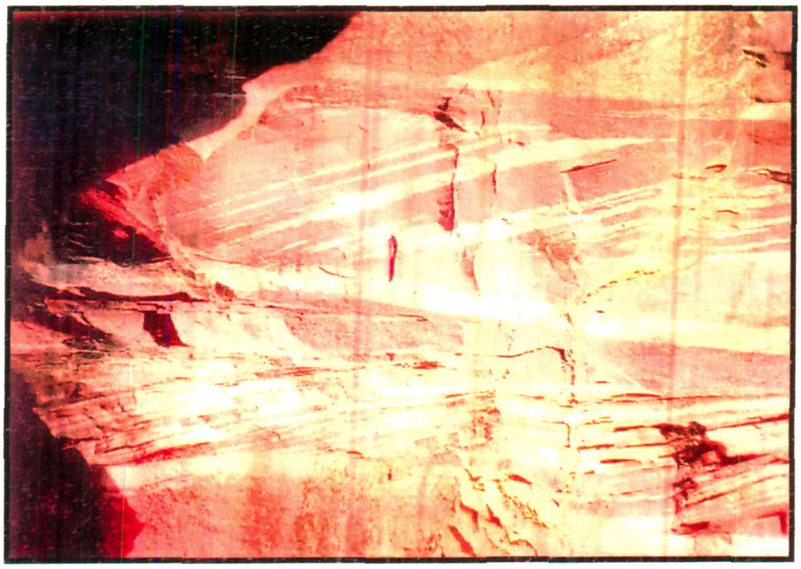
Figure 6 . Lithostratigraphic section measured near Rupbas village.

PLATE II



A

B



C

PLATE II

A. Field photograph showing large scale trough cross-bedding.

B, C. Field photograph showing large scale tabular cross-bedding.

Ghatouli Village Section

A Lithostratigraphic section was measured at the Ghatouli village, 11.5m thick (Figure 7) and is composed of sandstone and shale. The section shows large tidal channels. The section measured has the following sequence:

11.5-10.0 m	Pinkish white colored, fine grained, hard, tabular cross-bedded sandstone, lower contact is wavy, 1.5m thick.
10.0-9.0 m	Pinkish white colored, fine grained, soft, laminated sandstone with bed showing pinching and swelling, upper contact is wavy and lower contacts is undulatory,1.0m thick
9.0-7.0 m	Pink colored, fine grained, hard, tabular cross-bedded sandstone, lower and upper contacts undulatory, 2.0m thick.
7.0-6.5 m	Red colored, very fine grained shale, soft and having straight contact, 0.5m thick.
6.5-6.0 m	Red colored, medium grained, soft, tabular cross-bedded sandstone with channel body, sharp contact, 1.4m thick.
6.0-5.0 m	Red colored, medium grained, hard and compact, trough cross-bedded sandstone with presence of some clay galls, sharp contact,1.0m thick.
5.0-4.0 m	Red colored, medium grained, soft, small scale tabular cross-bedded sandstone, sharp and straight contact, 1.0m thick.

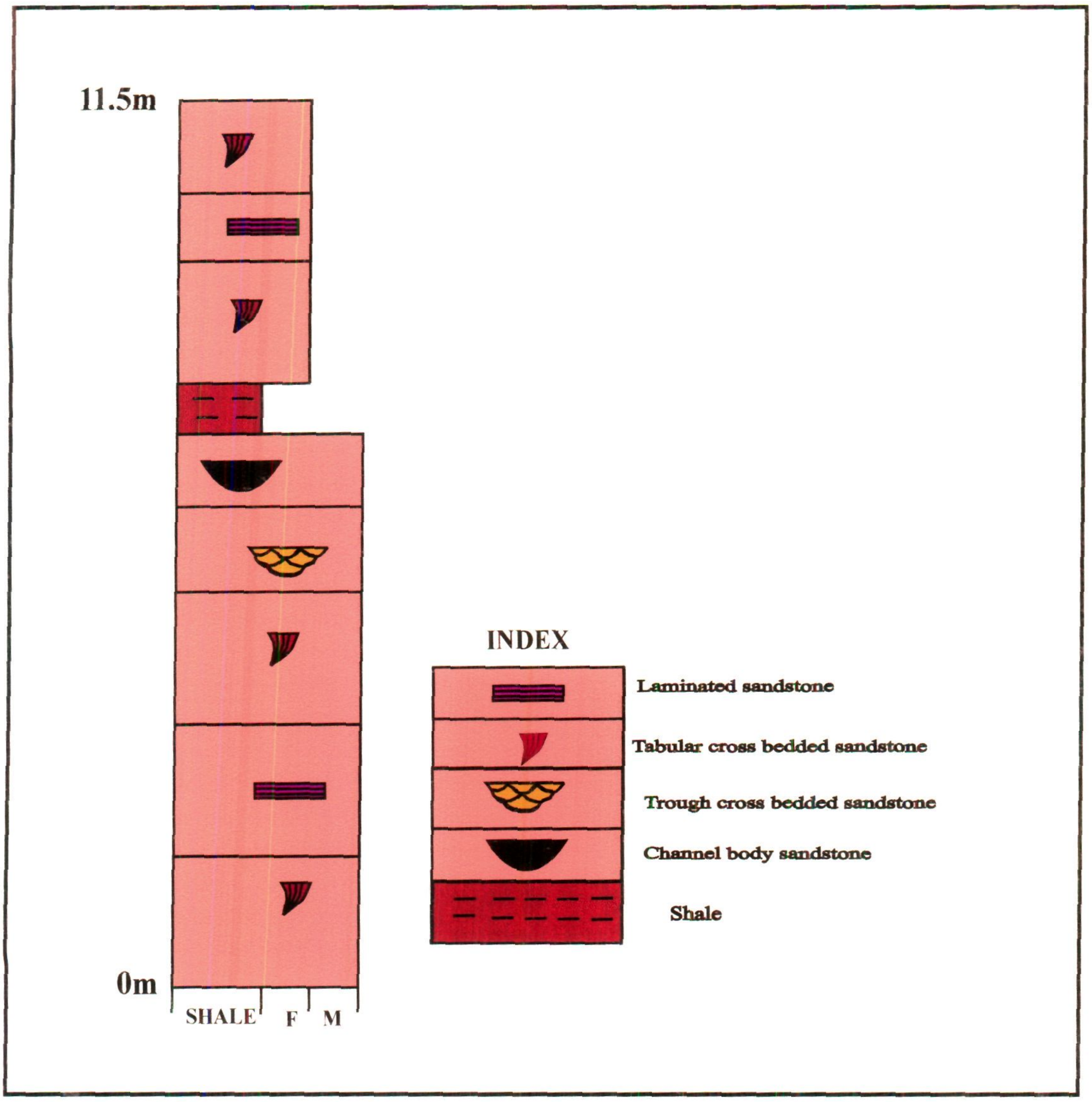


Figure 7 . Lithostratigraphic section measured near Ghatouli village.

4.0-2.0 m	Pink colored, medium grained, hard, thinly bedded laminated sandstone, sharp contact, 2.0m thick.
2.0-0 m	White colored, medium grained, hard and compact, large scale tabular cross-bedded sandstone with presence of clay pellets,
Bottom	sharp contact, 2.0m thick.

Mewali Village Section

A Lithostratigraphic section was measured at the village Mewali. 16.1m thick (Figure 8) and is composed of sandstone and shale. The measured section has the following sequence:

Top

16.1-14.0 m	Red colored, medium grained, soft, small scale tabular cross-bedded sandstone, sharp contact, 2.1m thick.
14.0-12.0 m	Red colored, medium grained, soft, large scale trough cross-bedded sandstone, straight contact,2.0m thick.
12.0-10.0 m	Red colored, medium grained, hard and compact, herringbone cross-bedded sandstone, sharp contact,2.0m thick.
10.0-8.5 m	Red colored, fine grained, hard and compact shale, sharp contact, 2.0m thick.
8.5-8.0 m	Red colored, fine grained, hard and compact, thinly laminated sandstone, straight contact, 0.5m thick.

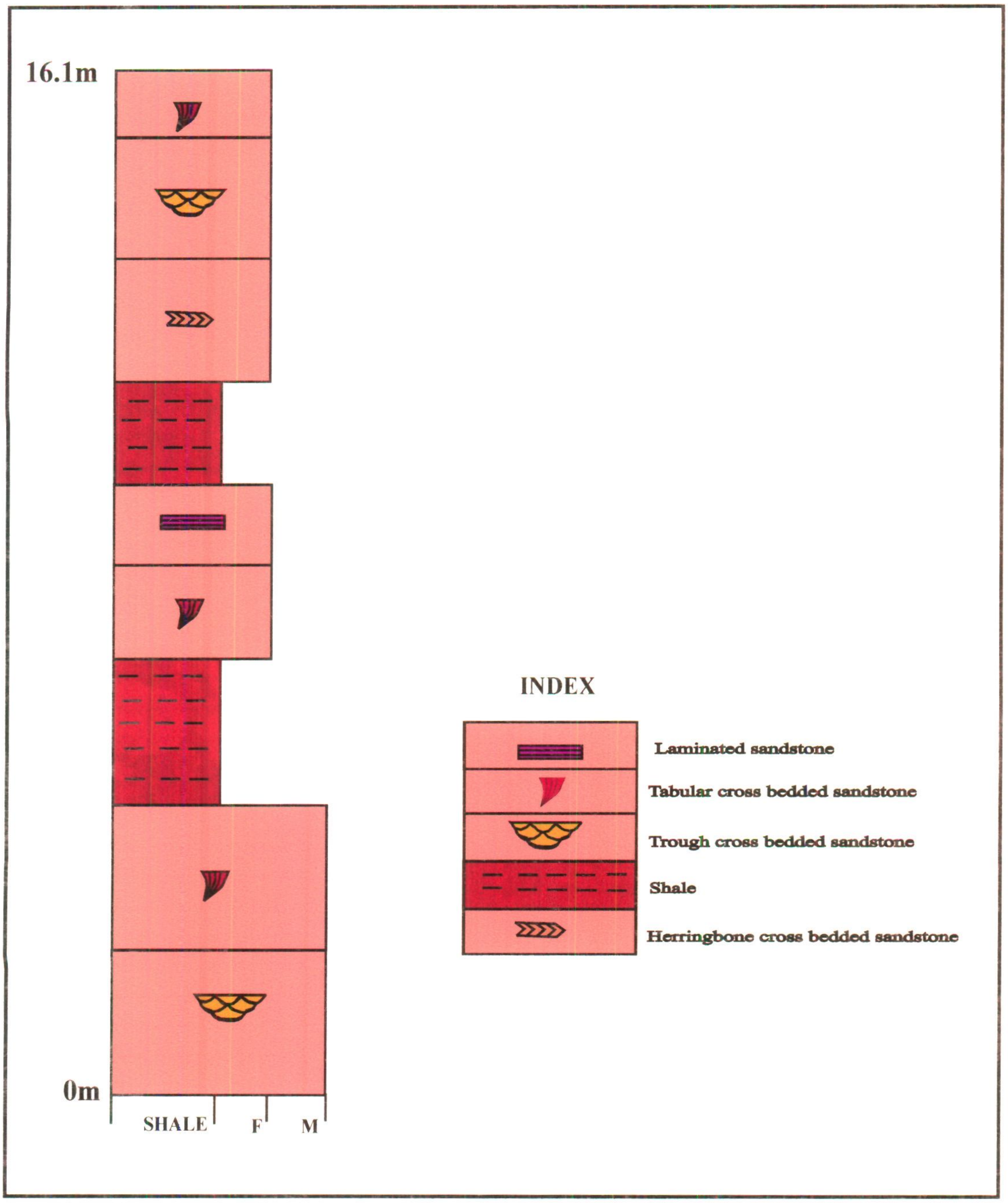


Figure 8. Lithostratigraphic section measured near Mewali village.

8.0-7.0 m	Red colored, fine, soft, large scale tabular cross-bedded sandstone, sharp contact,1.0m thick.
7.0-5.0 m	Red colored, fine grained, hard and compact shale, sharp contact, 2.0m thick.
5.0-3.0 m	White colored, medium grained, soft, tabular cross-bedded sandstone, sharp contact, 2.0m thick.
3.0-0 m	Red colored, medium grained, hard and compact, large scale trough-cross bedded sandstone, cross beds are in cosets, sharp
Bottom	contact, 1.2m thick.

Jagnair Village Section

A Lithostratigraphic section was measured at the village Jagnair, 10.5m thick (Figure 9) and is composed of sandstone and shale. The measured section has the following sequence:

Top

10.5-9.5 m	Pinkish white colored, fine grained, soft, tabular cross-bedded sandstone, straight contact, 1.0m thick.
9.5-9.0 m	Red colored, very fine grained, very soft shale, straight contact, 1.0m thick.
9.0-8.0 m	Red colored, fine grained, soft, tabular cross-bedded sandstone, straight contact, 1.0m thick.

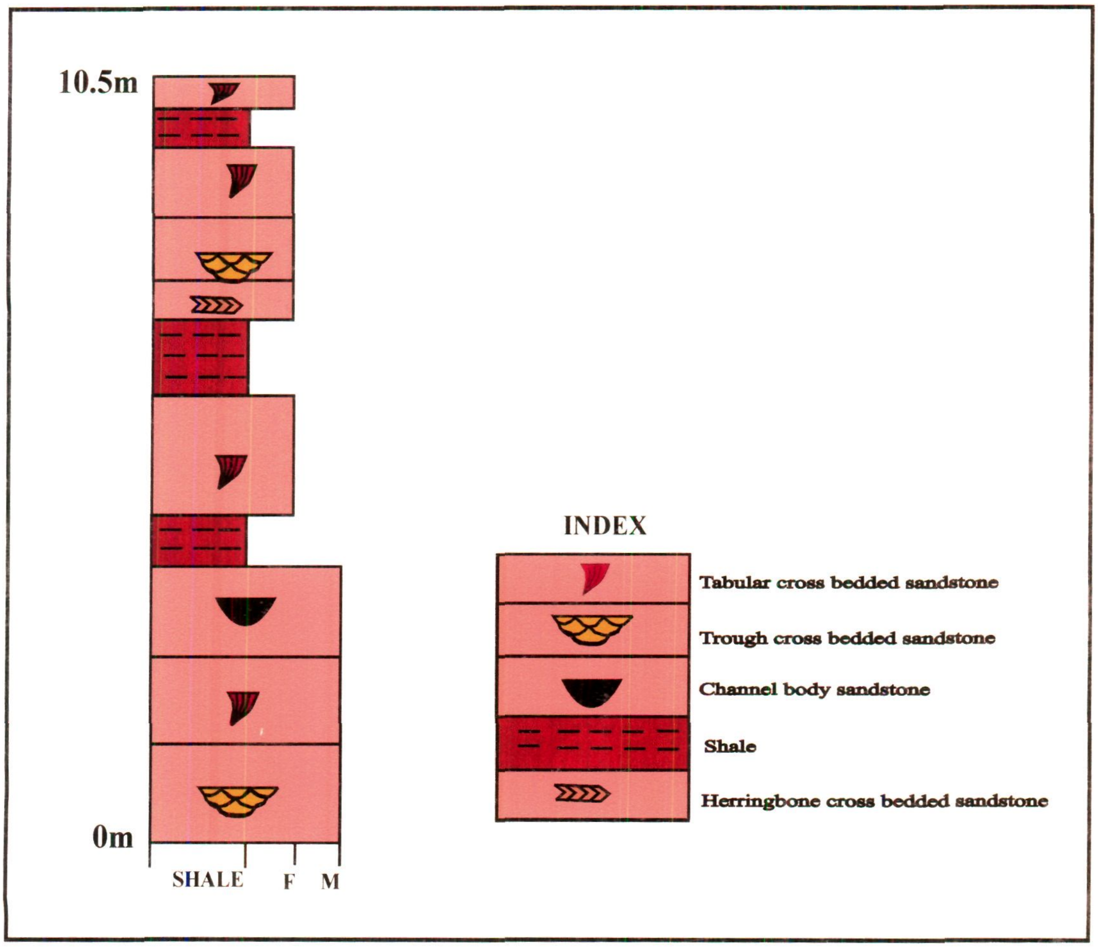


Figure 9 . Lithostratigraphic section measured near Jagnair village.

8.0-7.5 m	Red colored, fine grained, hard, massive sandstone with occasional small scale trough cross bedding and laminations, sharp contact, 0.5m thick
7.5-7.0 m	Red colored, fine grained, soft, small scale tabular cross bedded with presence of herringbone cross bedded sandstone, sharp contact, 0.5m thick.
7.0-5.5 m	Red colored, very fine grained, soft, shale, straight contact, 1.5m thick.
5.5-4.5 m	White colored, fine grained, soft, small scale tabular cross bedded sandstone, sharp contact, 1.0m thick.
4.5-4.0 m	Red colored, very fine grained, very soft shale, straight contact, 0.5m thick.
4.0-3.0 m	Pinkish white colored, medium grained, soft, tabular cross-bedded with large channel sand body, sharp contact,1.0m thick.
3.0-2.0 m	Pinkish white colored, medium grained, soft, small scale tabular cross-bedded sandstone, straight contact, 1.0m thick.
2.0-0 m Bottom	Pinkish white colored, medium grained, soft, small scale trough cross-bedded sandstone, straight contact, 2.0m thick.

Holipura Village Section

A Lithostratigraphic section was measured at the Holipura village is 4.3m thick (Figure 10) and is composed of sandstone. This section shows large tidal channel. The measured section has the following sequence:

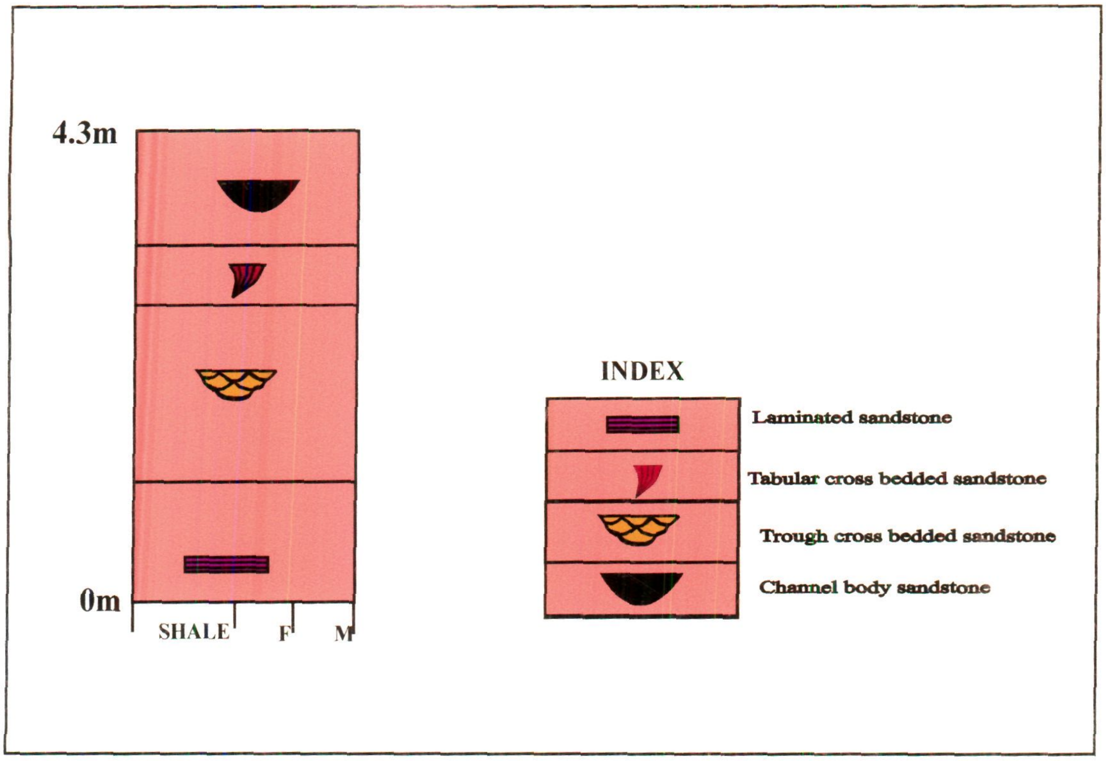


Figure 10 . Lithostratigraphic section measured near Holipura Village.

Top

4.3-3.5 m Red colored, medium grained, soft, large scale tabular cross-bedded with channel sand body, 0.8m thick.

3.5-3.0 m Red colored, medium grained, soft, large scale tabular cross-bedded sandstone with foreset thickness of beds 5-8cm, sharp contact, 0.5m thick.

3.0-1.0 m Red colored, medium grained, soft, large scale trough cross-bedded sandstone, lower and upper contacts are erosional, 2.0m thick.

1.0-0 m Red colored, medium grained, hard and compact, laminated flat

Bottom bedded sandstone, sharp contact, 1.0m thick.

Tantpur Section

There are several quarries located 2km southwest of Tantpur railway station. A Lithostratigraphic section was measured at the Tantpur quarry, 18.7m thick (Figure 11) and is composed of sandstone. The measured section has the following sequence:

Top

18.7-15.0 m White spotted red colored, medium grained, hard, laminated channel sand body, straight contact, 3.7m thick.

15.0-12.0 m White spotted red colored, medium grained, hard, tabular cross-bedded sandstone, sharp contact,3.0m thick

12.0-9.0 m	Red colored, medium grained, hard, finely laminated sandstone, sharp contact, 3.0m thick.
9.0-6.5 m	Red colored, medium grained, soft, tabular cross-bedded with white colored large channel body having convex shape (due to erosion) flat bedded sandstone, sharp contact, 2.5m thick.
6.5-6.0 m	Red colored, medium grained, soft, tabular cross-bedded sandstone, upper contact is sharp and lower contact is erosional, 0.5m thick.
6.0-4.0 m	White spotted red colored, medium grained, hard, trough cross-bedded sandstone, upper contact erosional and lower contact is sharp, 2.0m thick.
4.0-1.5 m	Red colored, medium grained, soft, thin laminated flat bedded sandstone, upper contact is sharp and lower contact is wavy, 2.5m thick.
1.5-0.5 m	White colored, medium grained, soft, tabular cross bedded sandstone, sharp contact, 1.0m thick.
0.5-0 m <u>Bottom</u>	Red colored, medium grained, soft, finely laminated sandstone, sharp contact, 0.5m thick.

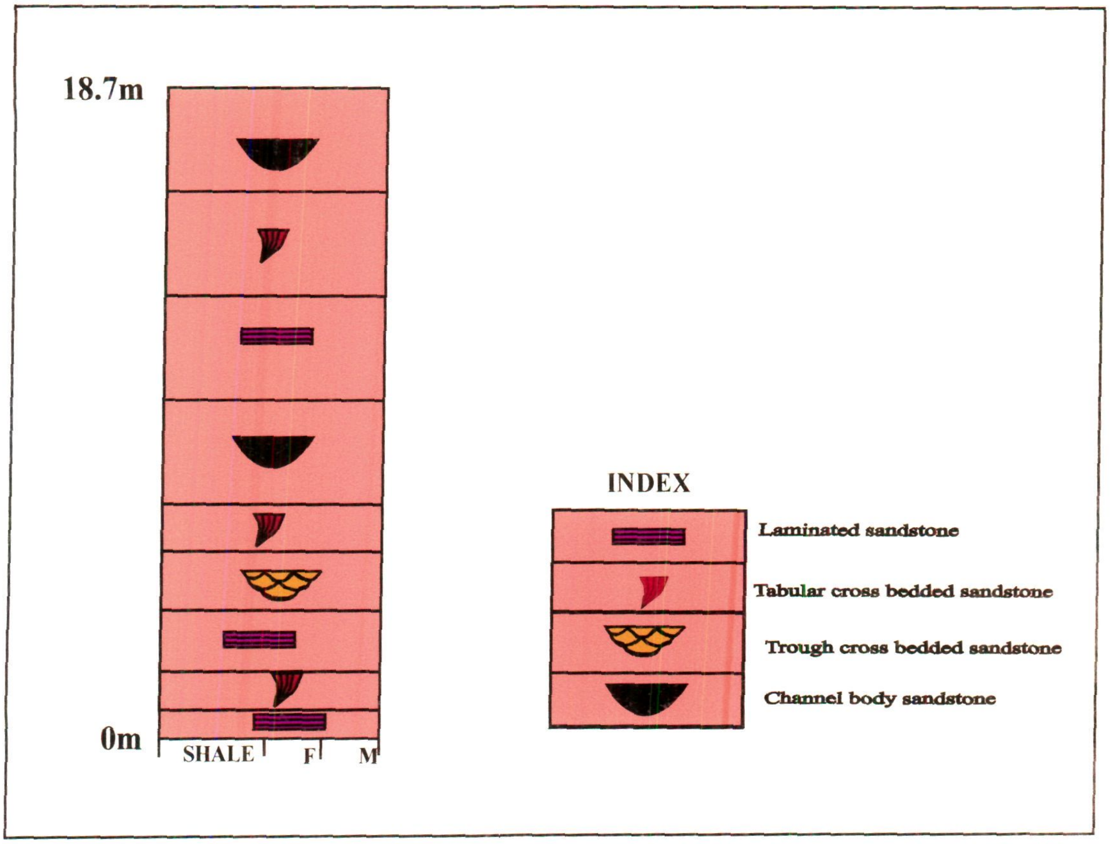


Figure 11. Lithostratigraphic section measured near Tantpur.

Baretha Village Section

A Lithostratigraphic section was measured at the Baretha village is 24.9m thick (Figure 12) and is composed of sandstone and shale. Pinching and swelling is common in this section. The measured section has the following sequence:

Top

24.9-23.5 m	White colored, medium grained, hard and compact, thickly bedded, laminated sandstone, sharp contact,1.4m thick.
23.5-22.0 m	Pinkish white colored, medium grained , soft, ripple bedded sandstone, straight contact, 1.5m thick.
22.0-21.0 m	White colored, medium grained, hard, thickly bedded, laminated, sandstone, sharp contact,1.0m thick.
21.0-20.0 m	White colored, medium grained, hard, thinly bedded, ripple bedded sandstone, pinching and swelling is common, sharp contact, 1.0m thick.
20.0-19.0 m	White colored, medium grained, hard, thinly bedded, laminated, pinching and swelling is common, sharp contact, 1.0m thick.
19.0-17.0 m	Red colored, medium grained, soft, asymmetrical ripple bedded sandstone, sharp contact,2.0m thick.
17.0-15.5 m	Red colored, medium grained, hard, laminated sandstone, silicification of beds is present, sharp contact, 1.5m thick.

15.5-15.0 m	White colored, medium grained, hard, tabular cross-bedded sandstone, pinching and swelling common, sharp contact,0.5m thick.
15.0-14.5 m	Red colored, very fine grained, soft shale, straight contact, 0.5m thick (Plate IIIA).
14.5-13.5 m	Red colored, fine grained, hard, tabular cross-bedded sandstone, sharp contact,1.0m thick.
13.5-12.5 m	Red colored, fine grained, hard, small scale trough cross-bedded sandstone ,silicification of beds is present , sharp contact, 2.0m thick.
12.5-12.0 m	Red colored, fine grained, hard, herringbone cross bedded sandstone, sharp contact, 0.5m thick (Plate IIIB).
12.0-11.0 m	Red colored, fine grained, soft friable shale, straight contact, 1.0m thick.
11.0-9.0 m	Red colored, fine grained, hard, laminated, trough cross-bedded sandstone with presence of clay galls giving an appearance of true intraformational shale pebble conglomerate, sharp contact, 2.0m thick.
9.0-7.0 m	Red colored, fine grained, hard, parallel laminated sandstone, sharp contact,2.0m thick.
7.0-6.5 m	Red colored, fine grained, soft, small scale tabular cross bedded, parallel laminated sandstone, sharp contact, 0.5m thick.

6.5-5.5 m	Red colored, fine grained, soft friable shale, straight contact, 1.0m thick.
5.5-5.0 m	Red colored, medium grained, hard, channel sandstone body, sharp contact, 0.5m thick (Plate IIIC).
5.0-3.0 m	Red colored, medium grained, hard, tabular cross-bedded sandstone, sharp contact,2.0m thick.
3.0-2.5 m	Red colored, medium grained, hard, parallel laminated sandstone, sharp contact,0.5m thick.
2.5-2.0 m	Red colored, medium grained, hard, trough cross-bedded sandstone ,sharp contact, 0.5m thick.
2.0-1.0 m	Red colored, medium grained, soft, small scale tabular cross-bedded sandstone, sharp contact,1.0m thick.
1.0-0 m	Red colored, medium grained, hard, parallel laminated
<u>Bottom</u>	sandstone, sharp contact, 1.0m thick

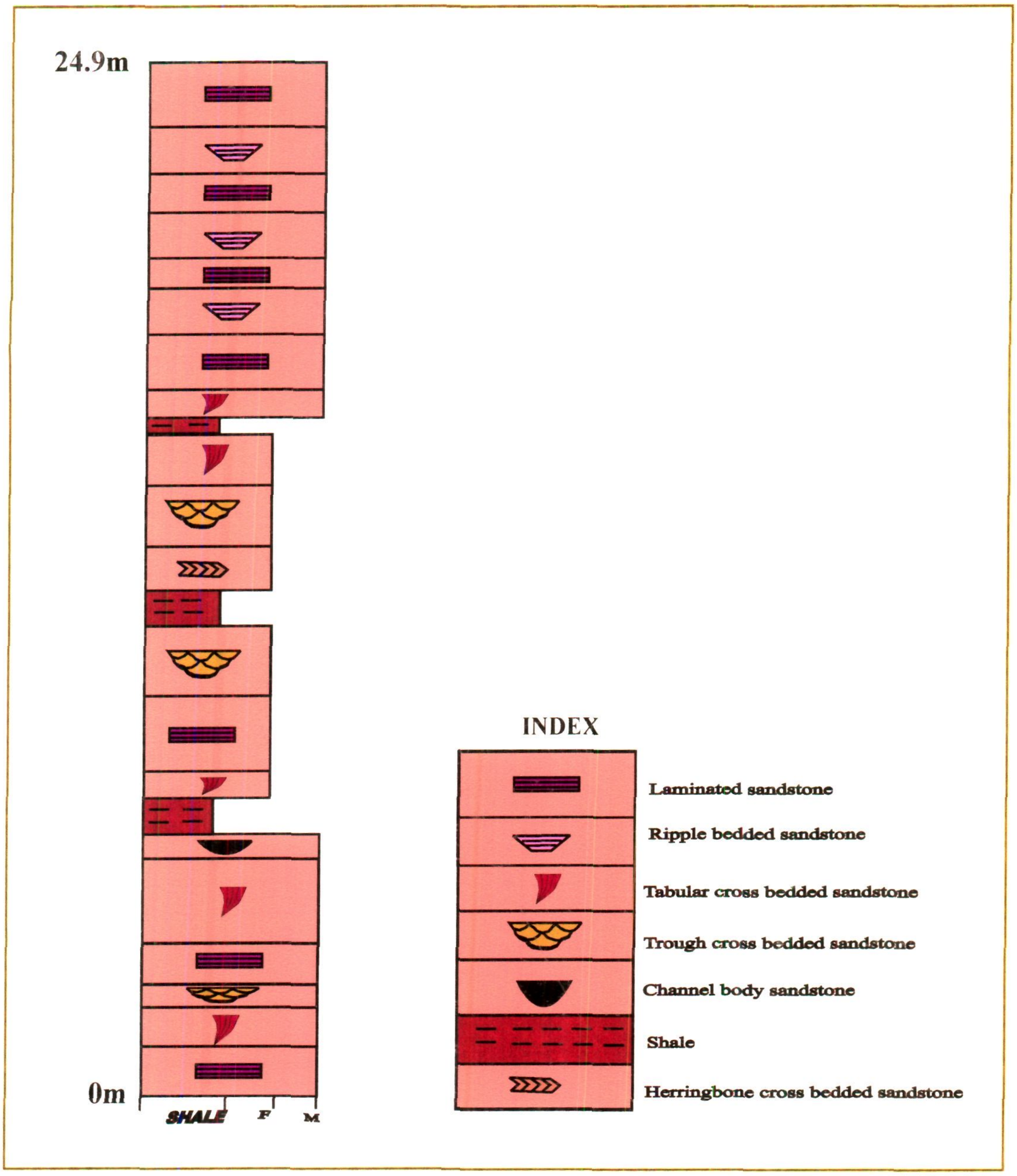


Figure 12. Lithostratigraphic section measured near Baretha village.

PLATE III

A

B

C

PLATE III

A. Field photograph showing thinly bedded shale.

B. Field photograph showing herringbone cross-bedded sandstone.

C. Field photograph showing large scale channel sandstone body.

Gchadi Bajana Village Section

A Lithostratigraphic section was measured at the Gchadi Bajana village, 26km towards Basodi having 8.3m thickness (Figure 13) and is composed of sandstone and shale. The measured section has the following sequence:

<u>Top</u>

8.3-7.0 m	Red colored, fine grained, hard, tabular cross-bedded sandstone with white colored laminated channel body, sharp contact,1.3m thick.
7.0-6.0	Red colored, fine grained, soft, laminated shale, straight contact, 1.0m thick.
6.0-5.5 m	Red colored, fine grained, hard, tabular cross-bedded sandstone with massive channel body, sharp contact, 0.5m thick.
5.5-5.0 m	Red colored, fine grained, hard, thinly bedded laminated sandstone, sharp contact, 0.5m thick.
5.0-4.5 m	Red colored, fine grained, soft, tabular cross bedded sandstone, sharp contact, 0.5m thick.
4.5-4.0 m	Red colored, very fine grained, soft shale, straight contact, 0.5m thick.
4.0-3.0 m	Red colored, medium grained, hard, tabular cross-bedded sandstone with massive channel body, sharp contact,0.5m thick.

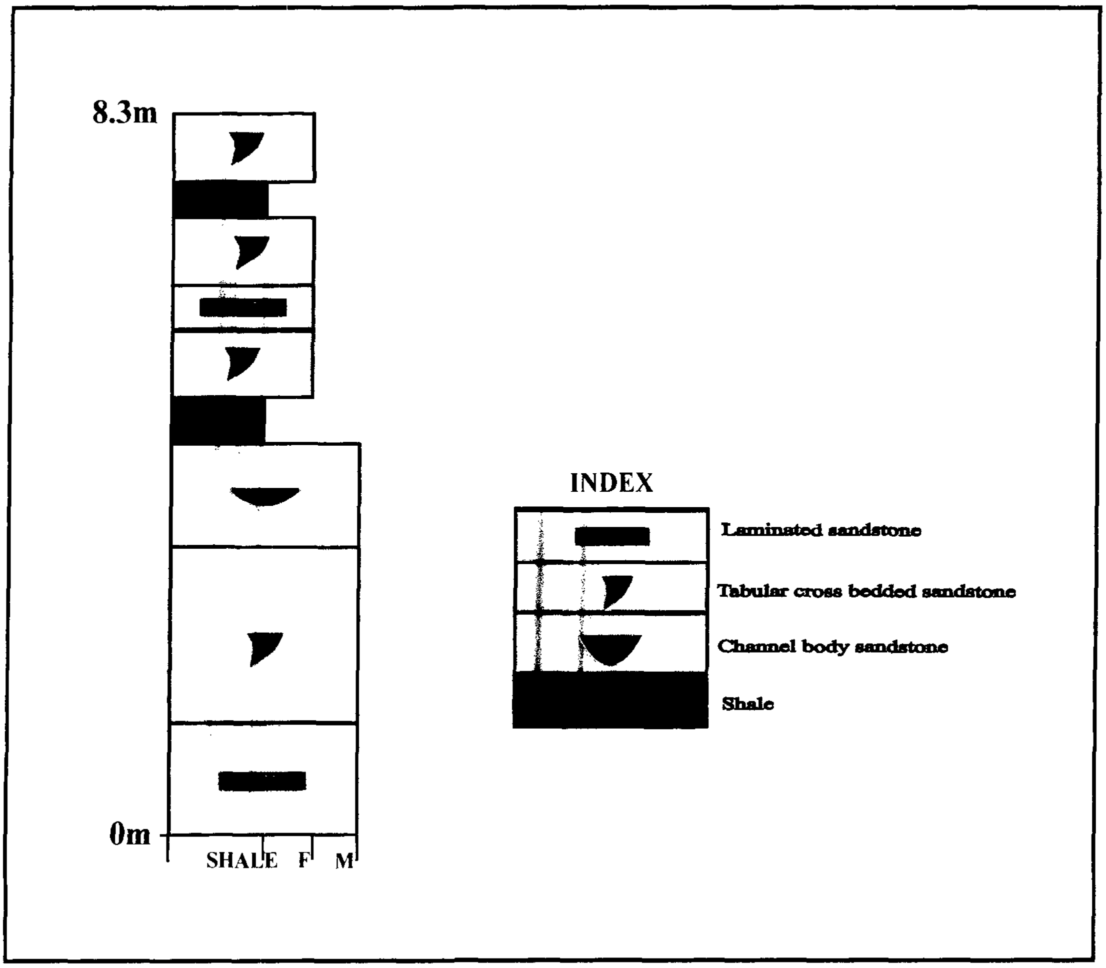


Figure 13 . Lithostratigraphic section measured near Gchadi Bajana village.

3.0-1.0 m Red colored, medium grained, soft, tabular cross-bedded sandstone, sharp contact, 2.0m thick.

1.0-0 m Red colored, medium grained, hard, thinly bedded laminated

Bottom sandstone, sharp contact, 1.0m thick.

Bansi Paharpur Village Section

A Lithostratigraphic section was measured along Bansi Paharpur village, 11.4m thick (Figure 14) and is composed of sandstone and shale. The section measured has the following sequence:

Top

11.4-10.5 m White colored, fine grained, hard, finely laminated sandstone, sharp contact, 0.9m thick.

10.5-10.0 m White colored, fine grained, hard and compact, tabular cross-bedded sandstone, sharp contact,0.5m thick.

10.0-9.5 m Red colored, very fine grained, soft shale, straight contact, 0.5m thick.

9.5-9.0 m White colored, fine grained, hard, thinly laminated, tabular cross- bedded sandstone with some small scale planar cross-bedding, sharp contact, 0.5m thick.

9.0-8.0 m White colored, fine grained, hard, trough cross-bedded sandstone, upper contact is wavy and lower contact is sharp, 1.0m thick.

8.0-7.0 m	White colored, fine grained, hard and compact, tabular cross-bedded sandstone with presence of herringbone, sharp contact, 1.0m thick.
7.0-6.0 m	Red colored, very fine grained, soft shale, straight contact, 0.5m thick.
6.0-5.0 m	White colored, fine grained, hard and compact, parallel laminated sandstone, sharp cont, 1.0m thick.
5.0-4.5 m	White colored, fine grained, hard and compact, tabular cross-bedded sandstone, sharp contact,0.5m thick.
4.5-3.5 m	Red colored, very fine grained, soft shale, straight contact, 1.0m thick.
3.5-3.0 m	Red colored, medium grained, hard, tabular cross-bedded sandstone with channel sand body, sharp contact,0.5m thick.
3.0-2.0 m	White colored, medium grained, hard and compact, tabular cross- bedded sandstone, sharp contact, 1.0m thick.
2.0-1.0 m	White colored, medium grained, hard, trough cross-bedded sandstone, contact sharp, 1.0m thick.
1.0-0 m <u>Bottom</u>	White colored, medium grained, hard and compact, thinly laminated sandstone, sharp contact, 1.0m thick.

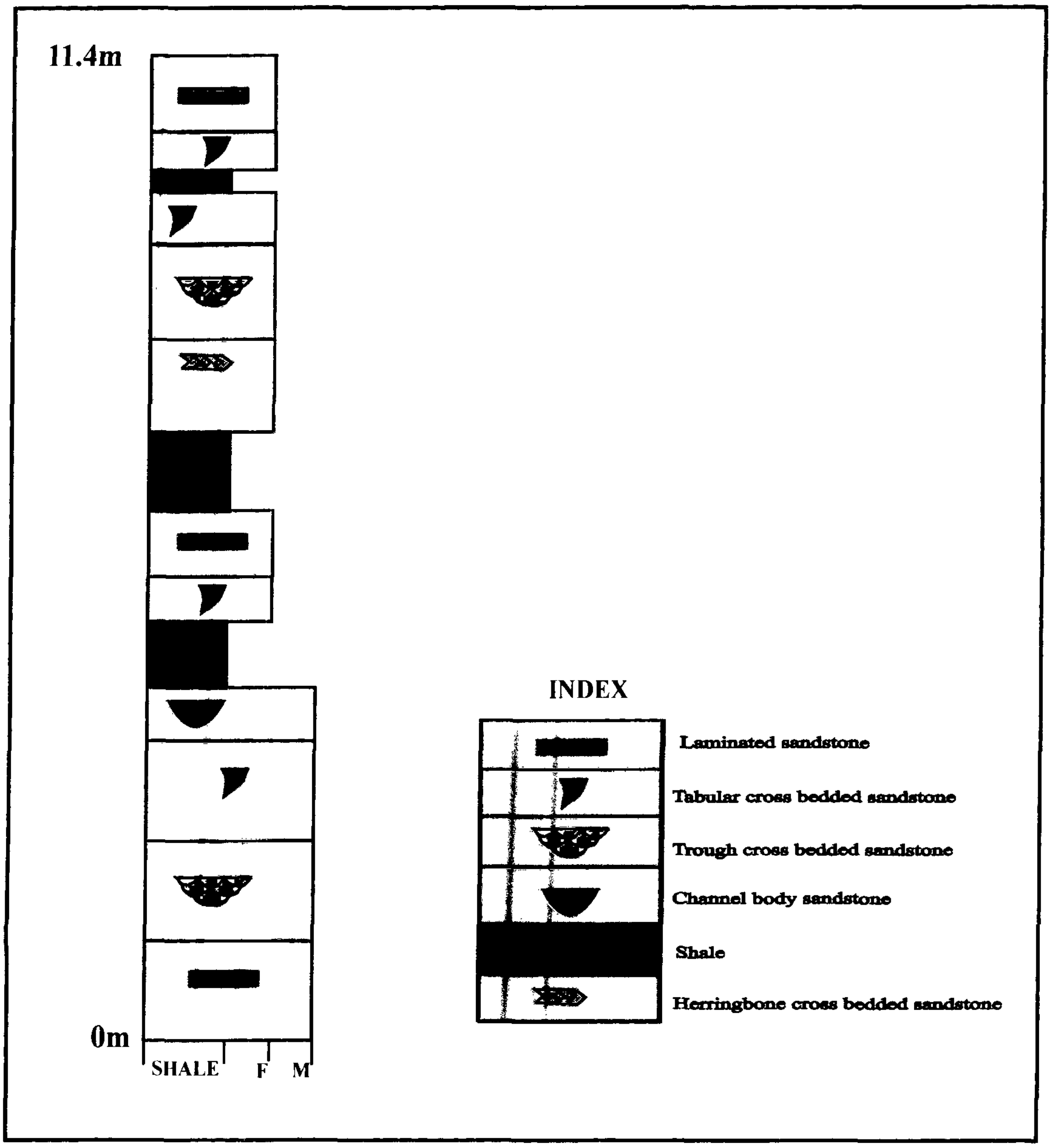


Figure 14 . Lithostratigraphic section measured near Bansi Paharpur village.

Rudawal Village Section

A Lithostratigraphic section was measured at the Rudawal village, 8.9m thick (Figure 15) and is composed of sandstone and shale. The section measured has the following sequence:

<u>Top</u>

8.9-8.0 m	White colored, medium grained, hard and compact, tabular cross-bedded sandstone, sharp contact, 0.9m thick .
8.0-7.5 m	White colored, medium grained, hard and compact, thinly laminated sandstone, sharp contact, 0.5m thick.
7.5-7.0 m	White colored, medium grained, hard, ripple bedded sandstone, sharp contact, 0.5m thick.
7.0-6.0 m	White colored, medium grained, hard, thinly laminated sandstone, sharp contact, 1.0m thick.
6.0-5.5 m	White colored, medium grained, hard, large scale ripple bedded sandstone, sharp contact, 0.5m thick
5.5-4.5 m	White colored, medium grained, hard, tabular cross-bedded sandstone, sharp contact,1.0m thick.
4.5-4.0 m	Red colored, very fine grained, soft shale, straight contact, 1.0m thick.
4.0-3.5 m	White colored, fine grained, soft, tabular cross bedded sandstone, jointed and fractured, sharp contact, 0.5m thick.

3.5-3.0 m	White colored, fine grained, hard, thinly bedded, laminated sandstone, sharp contact, 0.5m thick
3.0-1.0 m	White colored, fine grained, soft, tabular cross bedded sandstone, sharp contact, 2.0m thick.
1.0-0 m Bottom	Red colored, very fine grained, soft shale, straight contact, 1.0m thick.

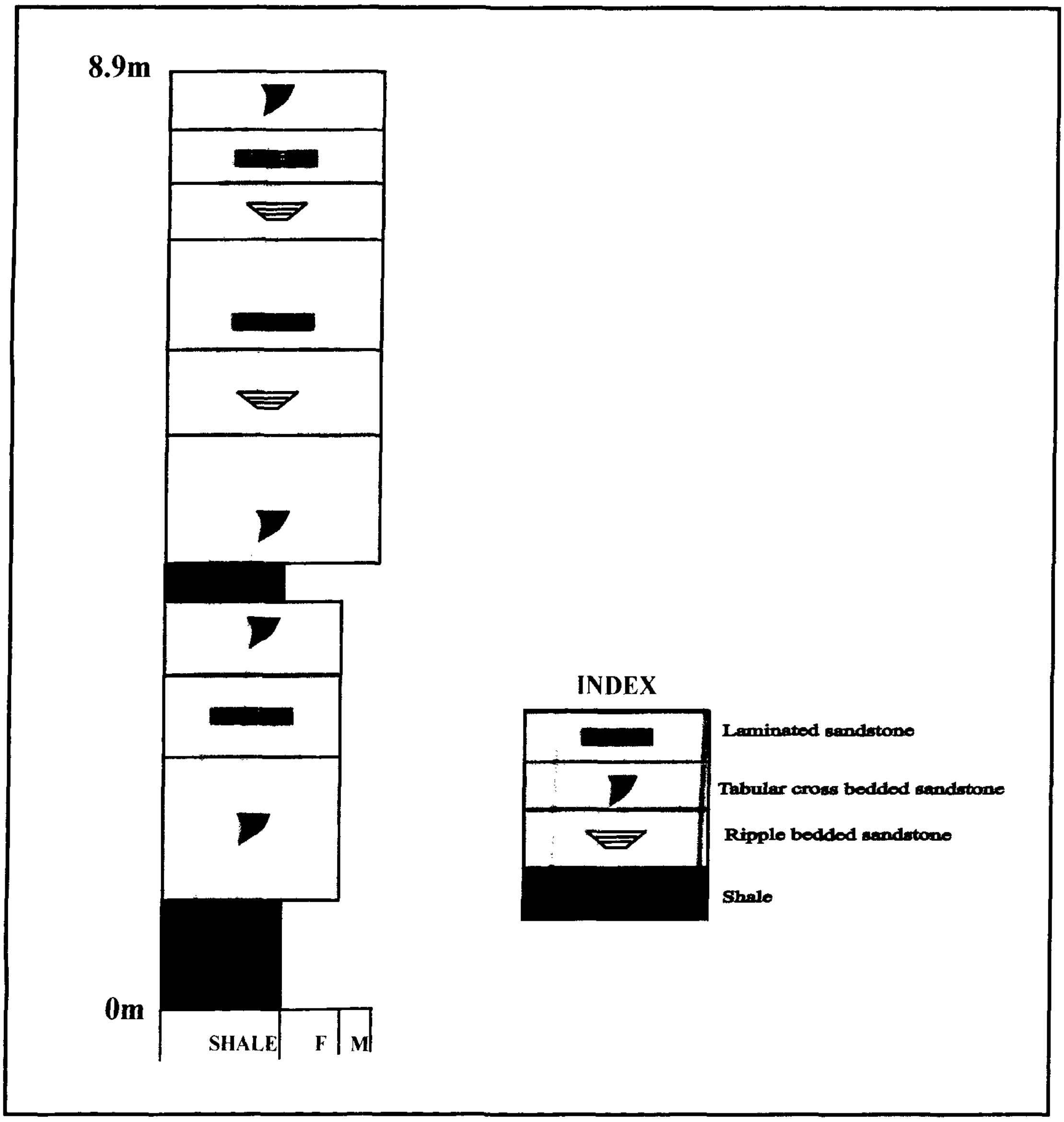


Figure 15. Lithostratigraphic section measured near Rudawal village.

CHAPTER - III

TEXTURE

INTRODUCTION

Textural attributes such as size, sorting, skewness, kurtosis, roundness and sphericity etc. of the Upper Bhander Sandstone were studied to interpret the provenance, environment of deposition, diagenesis and estimating the influence of texture on detrital modes and petrofacies. The interrelationships of various textural attributes of the Upper Bhander Sandstone were studied with the help of bivariant plots.

The study of grain size characteristics of sediment and their genetic interpretation have proved to be an interesting and challenging task over the years. A large number of workers have studied this aspect and produced voluminous literature. Reviews of grain size parameters and their relationship with depositional processes have been published by Folk (1966), Visher (1969) and Friedman (1979). Besides these workers Blatt (1967), Yong et al., (1975), Basu (1976), Mack and Suttner (1977) demonstrated the dependence of sandstone detrital modes on grain size.

Roundness is the property of sand grains that has significance for the study of the effect of the transportation process on the debris furnished by the source area. Roundness reveals the modification of angular grains of many shapes by abrasion, solution and current sorting. The roundness in particular reflects abrasion history which in turn depends upon diverse geological controls viz., relief, source rock, distance, mechanism and agency of transport and mineralogy of the grains. The change of roundness with distance is proportional to some power of the distance traveled. Various studies have shown that initially roundness increases vigorously with distance of travel and subsequently slower down. Sphericity of grains influences on the hydrodynamical behavior of particles, affecting its settling velocity and mode of transport in a fluid current and thus it effects selective transportation. The concept of sphericity was developed by Wadell (1935) who attributed it to be a measures of the degree to which a particle approaches a spherical shape.

METHODOLOGY

Thin sections were used in this study for grain size analysis and estimation of roundness and sphericity. Thin sections showing the least modification of texture by diagenetic and compaction effects were selected. These constraints limited the textural study to 105 samples of sandstones out of total collected 200 samples.

Grain size measurements were carried out with the help of a micrometer eye piece. Chayes (1949) point counting technique was employed and 150-200 grains were measured in each thin section. The size data was grouped into half-phi class interval. Cumulative frequency curves of grain size data were plotted on log probability paper. The grain diameters in phi units represented by $\Phi 5$, $\Phi 16$, $\Phi 25$, $\Phi 50$, $\Phi 75$, $\Phi 84$, and $\Phi 95$ percentiles were read from the size frequency curves. These values were then converted to their sieve equivalents with the help of Friedman's (1958).

In the present study roundness scale given by Powers (1953) with six roundness classes has been used. Mean roundness of each sample were determined by conventional statistical method employing the Powers class limit values. Roundness of the sand grains of each sample was measured by counting an average of about 100 grains per thin section. Sphericity of detrital particles was classified as low, medium and high according to the comparison chart given by Krumbein and Sloss (1963).

STATISTICAL PARAMETERS OF GRAIN SIZE

The statistical parameters of grain size were calculated according to formula given by Folk (1980) and included graphic mean **(MZ)**, Inclusive graphic standard deviation **(σI)**, inclusive graphic skewness **(SKI)**, graphic kurtosis **(KG).**

Graphic Mean Size (MZ)

$$MZ = \Phi 16 + \Phi 50 + \Phi 84/3$$

MZ of various samples ranges from 1.15 to 4.48, averages 2.45 (Table 2). Out of 105 studied sandstone samples, 81% of samples are medium grained and 19% of samples are fine grained. Mean size is the function of size range of available sediment and the amount of energy imported to the sediments which depend on current velocity or turbulence of the transporting medium.

Inclusive Graphic standard Deviation (σI)

$$\sigma I = (\Phi 84 - \Phi 16)/4 + (\Phi 95 - \Phi 5)/6.6$$

σI of the samples ranges from 0.49 to 1.35, averages 0.81 (Table 2). Out of 105 samples 55% samples are moderately sorted, 28% are moderately well sorted, 14% are poorly sorted and 3% well sorted. No systematic variation in sorting is observed at different localities "σI fluctuaties within the moderately and moderately well sorted fields".

Inclusive Graphic Skewness (SKI) and Graphic Kurtosis (KG)

$$SKI = (\Phi16 + \Phi84 - 2\,\Phi50)/2(\Phi84 - \Phi16) + (\Phi5 + \Phi95 - 2\Phi50)/2(\Phi95 - \Phi5).$$

$$KG = (\Phi95 - \Phi5)/2.44(\Phi75 - \Phi25).$$

SKI measures the degree of asymmetry of the frequency distribution and is determined by the relative importance of the tails of the distribution. The skewness or asymmetry is also determined by the position of the mean with respect to medium. SKI of the studied samples ranges from 0.57 to 1.90, averages 1.02 (Table 2). The samples are mainly strongly finely skewed.

Graphic Kurtosis reflects the peakedness of the distribution and measures the ratio between sorting in the tails of the curve and the sorting in the central portion. If the central portion is better sorted than the tail, the curve is said to be exclusively peaked or leptokurtic. When tails are better sorted than the central portion, the curve is flat peaked and platykurtic. KG of the studied samples ranges from 0.48 to 1.89, average 0.94 (Table 2). Out of 105 samples, 44 samples are mesokurtic, 41 platykurtic, 15 leptokurtic, 4 very platykurtic and one very leptokurtic.

Table 2. Statistical parameters for grain size distribution of the Upper Bhander Sandstone in parts of Uttar Pradesh-Rajasthan States.

Sample No.	Inclusive Graphic Mean (Mz)		Inclusive Graphic Standard Deviation (σ1)		Inclusive Graphic Skewness (SKI)		Graphic Kurtosis (KG)	
	Mz	Verbal Limit	σ1	Verbal Limit	SKI	Verbal Limit	KG	Verbal Limit
Rasulpur Section								
R1	2.33	Medium grained	0.75	Moderately sorted	0.96	Strongly fine skewed	1.31	Leptokurtic
R2	2.45	Medium grained	1.15	Poorly sorted	0.93	Strongly fine skewed	0.98	Mesokurtic
R3	1.25	Medium grained	0.72	Moderately sorted	0.81	Strongly fine skewed	1.01	Mesokurtic
R4	2.1	Medium grained	1.09	Poorly sorted	0.95	Strongly fine skewed	1.04	Mesokurtic
R5	2.26	Medium grained	1.09	Poorly sorted	0.95	Strongly fine skewed	1.24	Leptokurtic
R6	2.5	Medium grained	1.26	Poorly sorted	1	Strongly fine skewed	0.68	Platykurtic
R7	1.6	Medium grained	0.83	Moderately sorted	1.32	Strongly fine skewed	0.96	Mesokurtic
R8	1.7	Medium grained	1	Moderately sorted	0.93	Strongly fine skewed	1.08	Mesokurtic
R9	1.93	Medium grained	0.95	Moderately sorted	0.97	Strongly fine skewed	1.06	Mesokurtic
R10	2.64	Medium grained	1.22	Poorly sorted	1	Strongly fine skewed	0.95	Mesokurtic
R11	2.65	Medium grained	1.14	Poorly sorted	0.99	Strongly fine skewed	1	Mesokurtic
R12	2.33	Medium grained	1.35	Poorly sorted	0.98	Strongly fine skewed	1.1	Mesokurtic
R13	1.75	Medium grained	0.83	Moderately sorted	0.94	Strongly fine skewed	1	Mesokurtic
Tehra Section								
T-1	2.48	Medium grained	1.07	Poorly sorted	1.07	Strongly fine skewed	1.13	Leptokurtic
T-3	2.3	Medium grained	0.73	Moderately sorted	1.02	Strongly fine skewed	1.02	Mesokurtic

T-5	1.15	Medium grained	0.87	Moderately sorted	0.78	Strongly fine skewed	0.83	Platykurtic
T-6	3.16	Fine grained	0.89	Moderately sorted	1.18	Strongly fine skewed	0.60	Very Platykurtic
T-7	1.15	Medium grained	1.05	Poorly sorted	0.82	Strongly fine skewed	0.62	Very Platykurtic
T-8	2.36	Medium grained	0.90	Moderately sorted	1.19	Strongly fine skewed	0.57	Very Platykurtic
T-9	1.35	Medium grained	0.90	Moderately sorted	1.02	Strongly fine skewed	0.48	Very Platykurtic
T-10	1.36	Medium grained	1.04	Poorly sorted	0.97	Strongly fine skewed	0.80	Platykurtic
T-11	1.38	Medium grained	0.97	Moderately sorted	0.57	Strongly fine skewed	1.06	Mesokurtic
T-12	2.56	Medium grained	1.16	Poorly sorted	1.07	Strongly fine skewed	0.92	Mesokurtic
T-13	1.36	Medium grained	0.94	Moderately sorted	1.04	Strongly fine skewed	1.89	Very Leptokurtic
T-14	1.46	Medium grained	0.80	Moderately sorted	1.09	Strongly fine skewed	0.79	Platykurtic
Bakoli Section								
B1	2.3	Medium grained	0.91	Moderately sorted	0.96	Strongly fine skewed	1.08	Mesokurtic
B2	2.68	Medium grained	1.02	Poorly sorted	0.99	Strongly fine skewed	0.89	Platykurtic
B3	2.58	Medium grained	1.14	Poorly sorted	1.08	Strongly fine skewed	0.99	Mesokurtic
B4	2.45	Medium grained	0.73	Moderately sorted	1.10	Strongly fine skewed	1.25	Leptokurtic
B5	2.2	Medium grained	0.89	Moderately sorted	0.98	Strongly fine skewed	1.08	Mesokurtic
Rupbas Section								
RP1	2.76	Medium grained	0.89	Moderately sorted	1.74	Strongly fine skewed	1.14	Leptokurtic
RP2	3.05	Fine grained	0.96	Moderately sorted	1.05	Strongly fine skewed	0.73	Platykurtic
RP3	2.73	Medium grained	0.69	Moderately Well sorted	0.77	Strongly fine skewed	0.94	Mesokurtic

RP4	3.05	Fine grained	0.96	Moderately sorted	1.05	Strongly fine skewed	0.73	Platykurtic
RP5	2.76	Medium grained	0.89	Moderately sorted	1.74	Strongly fine skewed	1.14	Leptokurtic
RP6	2.73	Medium grained	0.69	Moderately Well sorted	0.77	Strongly fine skewed	0.94	Mesokurtic
Gatouli Section								
GH1	2.18	Medium grained	0.78	Moderately sorted	1.22	Strongly fine skewed	0.87	Platykurtic
GH2	1.58	Medium grained	0.87	Moderately sorted	0.95	Strongly fine skewed	0.79	Platykurtic
GH3	1.81	Medium grained	0.71	Moderately Well sorted	0.64	Strongly fine skewed	0.86	Platykurtic
GH4	2.11	Medium grained	0.86	Moderately sorted	1	Strongly fine skewed	1.1	Mesokurtic
GH5	2.06	Medium grained	0.62	Moderately Well sorted	0.97	Strongly fine skewed	0.91	Mesokurtic
GH6	1.56	Medium grained	0.89	Moderately sorted	0.99	Strongly fine skewed	0.90	Platykurtic
Mewali Section								
M1	2.25	Medium grained	0.93	Moderately sorted	0.95	Strongly fine skewed	0.86	Platykurtic
M2	2.43	Medium grained	0.76	Moderately sorted	0.93	Strongly fine skewed	0.96	Mesokurtic
M3	2.66	Medium grained	0.90	Moderately sorted	1.08	Strongly fine skewed	0.97	Mesokurtic
M4	2.26	Medium grained	0.82	Moderately sorted	1.57	Strongly fine skewed	0.87	Platykurtic
M5	2.25	Medium grained	1	Moderately sorted	1	Strongly fine skewed	1.09	Mesokurtic
M6	1.73	Medium grained	0.79	Moderately sorted	0.90	Strongly fine skewed	1.02	Mesokurtic
M7	1.7	Medium grained	0.83	Moderately sorted	1.27	Strongly fine skewed	0.79	Platykurtic
Jagnair Section								
J1	1.98	Medium grained	0.69	Moderately Well sorted	0.99	Strongly fine skewed	1.05	Mesokurtic
J2	2.98	Medium grained	0.82	Moderately sorted	1	Strongly fine skewed	0.88	Platykurtic

J3	1.73	Medium grained	0.71	Moderately Well sorted	1.01	Strongly fine skewed	0.76	Platykurtic
J4	1.36	Medium grained	0.74	Moderately sorted	1	Strongly fine skewed	0.98	Mesokurtic
J5	1.16	Medium grained	0.71	Moderately Well sorted	1.02	Strongly fine skewed	0.67	Platykurtic
J7	2.1	Medium grained	0.66	Moderately Well sorted	0.95	Strongly fine skewed	1.06	Mesokurtic
Holipura Section								
HP1	3.35	Medium grained	0.92	Moderately sorted	1.90	Strongly fine skewed	0.84	Platykurtic
HP2	2.71	Medium grained	0.92	Moderately sorted	1.11	Strongly fine skewed	1.17	Leptokurtic
HP3	2.8	Medium grained	1.02	Poorly sorted	1.08	Strongly fine skewed	0.81	Platykurtic
Tantpur Section								
TT1	3.5	Fine grained	0.83	Moderately sorted	1	Strongly fine skewed	0.70	Platykurtic
TT2	2.8	Medium grained	0.49	Well sorted	0.18	Strongly fine skewed	1.02	Mesokurtic
TT3	3.45	Fine grained	0.76	Moderately sorted	1	Strongly fine skewed	0.75	Platykurtic
TT4	3.3	Fine grained	0.77	Moderately sorted	1.05	Strongly fine skewed	0.75	Platykurtic
TT5	2.78	Medium grained	0.76	Moderately sorted	0.97	Strongly fine skewed	1.08	Mesokurtic
TT6	2.91	Medium grained	0.94	Moderately sorted	0.97	Strongly fine skewed	1.15	Leptokurtic
TT7	2.68	Medium grained	1.02	Poorly sorted	0.93	Strongly fine skewed	0.91	Platykurtic
TT8	2.93	Medium grained	0.85	Moderately sorted	1.01	Strongly fine skewed	0.90	Platykurtic
Baretha Section								
BD1	2.76	Medium grained	0.49	Well sorted	1.02	Strongly fine skewed	1.06	Mesokurtic
BD2	2.91	Medium grained	0.59	Moderately Well sorted	1.03	Strongly fine skewed	0.91	Mesokurtic
BD3	3.30	Fine grained	0.72	Moderately sorted	1.02	Strongly fine skewed	0.82	Platykurtic

BD4	2.75	Medium grained	0.64	Moderately Well sorted	1.06	Strongly fine skewed	1.36	Leptokurtic
BD5	4.48	Fine grained	0.51	Moderately Well sorted	1	Strongly fine skewed	0.90	Platykurtic
BD6	3.03	Fine grained	0.62	Moderately Well sorted	0.98	Strongly fine skewed	1.10	Mesokurtic
BD7	3.1	Fine grained	0.68	Moderately Well sorted	1.06	Strongly fine skewed	0.78	Platykurtic
BD8	2.98	Medium grained	0.80	Moderately sorted	1.19	Strongly fine skewed	1.28	Leptokurtic
BD9	3.31	Fine grained	0.62	Moderately Well sorted	1.05	Strongly fine skewed	1.10	Mesokurtic
BD10	3.05	Fine grained	0.59	Moderately Well sorted	1.04	Strongly fine skewed	1.05	Mesokurtic
BD11	2.4	Medium grained	0.75	Moderately sorted	0.95	Strongly fine skewed	0.92	Mesokurtic
Gchadi Bajana Section								
G1	3.1	Fine grained	0.63	Moderately Well sorted	1.06	Strongly fine skewed	0.77	Platykurtic
G2	3.16	Fine grained	0.65	Moderately Well sorted	1.11	Strongly fine skewed	0.98	Mesokurtic
G3	2.98	Medium grained	0.61	Moderately Well sorted	1.05	Strongly fine skewed	0.82	Platykurtic
G4	2.9	Medium grained	0.59	Moderately Well sorted	1.1	Strongly fine skewed	1.18	Leptokurtic
G5	2.96	Medium grained	0.67	Moderately Well sorted	1.04	Strongly fine skewed	0.94	Mesokurtic
Bansi Paharpur Section								
BP1	3.08	Fine grained	0.77	Moderately sorted	1.11	Strongly fine skewed	1.15	Leptokurtic
BP2	3.16	Fine grained	0.60	Moderately Well sorted	0.92	Strongly fine skewed	1	Mesokurtic
BP3	3.28	Fine grained	0.75	Moderately sorted	1.03	Strongly fine skewed	0.89	Platykurtic
BP4	2.98	Medium grained	0.75	Moderately sorted	1.01	Strongly fine skewed	0.96	Mesokurtic
BP5	3.2	Fine grained	0.75	Moderately sorted	1.05	Strongly fine skewed	0.77	Platykurtic

BP6	3.23	Fine grained	0.60	Moderately Well sorted	1.01	Strongly fine skewed	0.84	Platykurtic
BP7	2.65	Medium grained	0.71	Moderately sorted	0.99	Strongly fine skewed	1.23	Leptokurtic
BP8	2.75	Medium grained	0.72	Moderately sorted	1.04	Strongly fine skewed	1	Mesokurtic
BP9	2.98	Medium grained	0.68	Moderately Well sorted	0.99	Strongly fine skewed	1.23	Leptokurtic
BP10	2.88	Medium grained	0.73	Moderately sorted	0.95	Strongly fine skewed	1.08	Mesokurtic
BP11	3.5	Medium grained	0.70	Moderately Well sorted	1.08	Strongly fine skewed	0.91	Mesokurtic
BP12	4.52	Fine grained	0.52	Moderately Well sorted	1	Strongly fine skewed	0.89	Platykurtic
BP13	3.36	Fine grained	0.72	Moderately sorted	0.99	Strongly fine skewed	0.87	Platykurtic
Rudawal Section								
RD1	1.48	Medium grained	0.67	Moderately Well sorted	1.07	Strongly fine skewed	0.70	Platykurtic
RD2	1.91	Medium grained	0.75	Moderately sorted	0.96	Strongly fine skewed	0.77	Platykurtic
RD3	1.78	Medium grained	0.84	Moderately sorted	0.96	Strongly fine skewed	0.96	Mesokurtic
RD4	1.6	Medium grained	0.69	Moderately Well sorted	1.04	Strongly fine skewed	0.70	Platykurtic
RD5	2.23	Medium grained	0.82	Moderately sorted	1.04	Strongly fine skewed	0.76	Platykurtic
RD6	1.56	Medium grained	0.72	Moderately sorted	0.98	Strongly fine skewed	0.73	Platykurtic
RD7	2.1	Medium grained	0.90	Moderately sorted	1.60	Strongly fine skewed	0.79	Platykurtic
RD8	1.58	Medium grained	0.69	Moderately Well sorted	1.04	Strongly fine skewed	1.12	Leptokurtic
RD9	1.76	Medium grained	0.69	Moderately Well sorted	1.02	Strongly fine skewed	0.80	Platykurtic
RD10	1.35	Medium grained	0.60	Moderately Well sorted	0.93	Strongly fine skewed	1.02	Mesokurtic
Average Area Level	2.45		0.81		1.20		0.94	

Skewness and kurtosis were referred to as indicators of selective action of transporting agent by Krumbein and Pettijohn (1938). Since then the parameters have been employed by various investigators to interpret depositional processes and environments. Folk and Ward (1957) suggested that sands deposited near the source are characteristically leptokurtic and positive skewed. Mason and Folk (1958) made a comparative textural studies of recent sands of beach, dune and aeolian flat environments. These studies indicated that beach sands are normal or negatively skewed and leptokurtic, dune sands have positive skewness and are mesokurtic, and aeolian flat sands are positively skewed and leptokurtic.

Friedman (1961) suggested that beach sands generally have negative skewness, but both dune and river sands usually have positive skewness. Duane (1964) demonstrated that the sands of the littoral, beach and tidal inlet environments have negative skewness as a result of winnowing action of waves and tidal currents. In sheltered quiet water areas and in deeper water, where bottom currents or wave base surge are not effective, the sands have positive skewness. Sediments show local variation in the sign of skewness in areas of fluctuating energy.

ROUNDNESS

Mean roundness of each samples of Upper Bhander Sandstone was determined by conventional statistical method employing the Powers class limit values. In various samples, roundness of grain ranges from very angular to well rounded.

However, in most samples majority of the grains are subangular to subrounded. The distribution of roundness in individual samples is invariably unimodal with subrounded as the modal class. The mean roundness of the individual samples ranges from 0.36 to 0.53, averages 0.44 (Table 3).

SPHERICITY

The most commonly used method of determining the sphericity is through visual comparison. For the present study the comparison chart given by Krumbein and Sloss (1963) was used for classification of sandstones into three classes, high, medium and low sphericity.

> 0.9 High sphericity
0.6 Medium
< 0.3 Low sphericity

The mean grain sphericity values of the Upper Bhander Sandstone ranges from 0.36 to 0.57, average 0.47 (Table 4).

TEXTURAL MATURITY

Textural maturity of the Upper Bhander Sandstone was determined employing Folk's (1980) concept of textural maturity. According to this concept, the sediments are subjected to mechanical energy through processes of abrasive and sorting action during transportation and subsequently pass through the four stages of maturity from immature to submature, mature and supermature stage.

Textural maturity gives most important clue to the physical nature of the depositional environments. It provides an idea about the effectiveness of the environment in winnowing, sorting and abrading in the detritus furnished to it. Thus the immature sediments accumulate in such environments where current

Table 3. Roundness of detrital grains of the Upper Bhander Sandstone in parts of Uttar Pradesh - Rajasthan States.

Sample No.	Very Angular (0.120.17)		Angular (0.17-0.25)		Subangular (0.25-0.35)		Subrounded (0.35-0.49)		Rounded (0.49-0.70)		Well Rounded (0.70-1.0)		Total Grains	Mean Roundness
	N	%	N	%	N	%	N	%	N	%	N	%		
Rasulpur Section														
R1	4	3	16	10	47	30	67	43	21	13	2	1	157	0.43
R2	2	2	6	5	36	33	50	45	14	13	2	2	110	0.44
R3	4	3	8	5	36	22	48	31	43	28	17	11	156	0.53
R4	5	3	6	3	68	39	56	32	29	17	10	6	174	0.45
R5	10	4	20	9	104	45	72	31	18	8	4	3	228	0.39
R6	5	1	28	9	103	35	118	40	39	13	1	2	294	0.42
R7	5	2	4	2	54	32	73	43	28	16	5	5	169	0.48
R8	8	3	6	2	72	34	60	30	47	22	14	9	207	0.45
R9	2	1	4	2	52	26	89	45	45	23	4	3	196	0.49
R10	8	6	6	5	45	37	35	35	16	15	5	2	115	0.43
R11	4	2	8	5	61	38	48	30	28	17	10	8	159	0.47
R12	5	4	5	3	44	34	50	39	19	14	5	7	128	0.45
R13	5	2	15	6	75	30	90	36	45	18	16	8	246	0.49
Tehra Section														
T-1	15	5	20	7	115	45	85	33	15	5	5	4	255	0.37
T-3	5	3	13	7	80	48	59	35	5	3	3	4	165	0.42
T-5	5	3	7	4	81	50	50	31	12	8	6	4	161	0.43
T-6	5	2	14	6	106	48	74	32	18	7	12	5	229	0.46
T-7	6	2	15	6	87	38	73	31	37	15	20	8	238	0.50
T-8	15	5	21	8	96	39	86	34	33	13	3	1	254	0.44
T-9	4	2	7	4	65	40	61	37	24	14	5	3	166	0.46
T-10	7	5	9	7	49	37	44	33	17	13	5	5	131	0.46
T-11	4	3	6	4	51	36	48	34	24	17	6	6	139	0.48
T-12	4	2	5	3	73	45	43	26	33	20	4	4	162	0.47
T-13	2	1	3	2	58	36	55	35	32	20	8	6	158	0.50
T-14	3	2	6	3	75	43	67	39	15	8	6	5	172	0.45
Bakoli Section														
B1	4	4	12	5	91	37	100	41	24	9	10	4	241	0.45
B2	8	5	10	6	75	47	55	34	12	7	2	1	162	0.41
B3	9	6	7	5	60	42	44	30	19	13	6	4	145	0.44
B4	4	1	3	1	110	37	105	35	54	18	22	8	298	0.51
B5	5	2	6	2	100	42	85	36	33	14	10	4	239	0.45
Rupbas Section														
RP1	5	2	14	6	75	38	90	43	18	8	6	3	208	0.43
RP2	4	1	22	9	80	36	92	39	25	10	12	5	235	0.45
RP3	4	2	17	7	80	36	95	42	21	9	10	4	227	0.45
RP4	5	2	14	6	75	38	90	43	18	8	6	3	208	0.43
RP5	4	1	22	9	80	36	92	39	25	10	12	5	235	0.45
RP6	4	1	17	7	80	37	95	42	21	9	10	4	227	0.45
Gatouli Section														
GH1	4	2	9	5	82	48	54	30	18	10	9	5	176	0.44
GH2	12	3	15	4	120	40	100	31	52	16	20	6	319	0.47
GH3	4	1	28	10	113	41	90	33	7	11	6	4	271	0.44

GH4	2	1	37	15	105	43	84	34	12	5	2	2	242	0.40
GH5	3	1	24	9	99	41	86	36	24	10	7	3	243	0.46
GH6	4	2	22	8	100	37	93	36	33	12	14	5	266	0.47
Mewali Section														
M1	3	2	20	11	65	33	80	41	18	9	7	4	193	0.44
M2	4	3	17	11	43	29	66	42	18	11	8	5	156	0.46
M3	4	2	16	8	60	32	81	42	20	10	12	6	193	0.46
M4	6	2	16	6	96	34	130	46	24	8	11	4	283	0.44
M5	5	2	20	10	70	30	90	39	27	12	16	7	228	0.46
M6	4	2	34	16	62	33	88	43	10	4	5	2	203	0.42
M7	4	2	15	8	67	38	82	43	13	6	7	3	188	1.12
Jagnair Section														
J1	4	2	16	8	81	41	71	35	20	10	8	4	200	0.44
J2	3	1	24	11	90	42	80	37	15	7	5	2	217	0.42
J3	5	2	18	5	137	46	109	34	35	11	8	2	312	0.44
J4	5	2	24	11	85	37	72	32	29	13	12	5	227	0.45
J5	6	3	27	12	80	37	69	32	25	11	11	5	218	0.46
J7	7	3	15	7	80	43	65	33	16	8	12	6	195	0.44
Holipura Section														
HP1	4	2	5	2	90	45	77	40	20	9	5	2	201	0.45
HP2	4	2	5	2	75	46	62	37	17	10	6	3	169	0.46
HP3	2	1	6	3	75	43	70	39	15	8	6	6	179	0.47
Tantpur Section														
TT1	6	2	26	8	145	50	91	31	22	7	5	2	295	0.41
TT2	11	4	29	11	120	44	85	31	20	7	7	3	272	0.42
TT3	3	1	48	16	107	38	105	35	21	7	10	3	294	0.42
TT4	4	1	19	6	139	48	107	36	24	8	3	1	296	0.45
TT5	8	4	21	9	90	41	70	32	28	12	5	2	222	0.43
TT6	5	2	32	10	132	43	109	34	22	7	5	4	314	0.44
TT7	4	1	34	12	121	45	90	33	17	6	9	3	275	0.41
TT8	3	2	27	14	76	42	64	34	10	5	6	3	186	0.42
Baretha Section														
BD1	8	3	68	22	105	36	96	31	18	5	10	3	305	0.51
BD2	7	3	54	22	90	39	67	27	17	6	8	3	243	0.42
BD3	8	3	45	19	86	38	66	28	19	8	10	4	234	0.43
BD4	7	3	43	19	90	41	61	27	16	7	9	3	226	0.42
BD5	5	3	32	19	58	31	49	32	14	7	10	8	168	0.43
BD6	6	2	16	23	126	38	97	29	18	5	6	3	329	0.38
BD7	5	3	28	18	69	44	47	30	6	4	3	1	158	0.38
BD8	5	3	32	19	58	35	49	29	14	8	10	6	168	0.43
BD9	6	2	57	23	84	36	76	31	14	5	6	3	243	0.39
BD10	10	4	50	21	78	35	69	30	17	7	6	3	230	0.40
BD11	6	2	44	19	83	39	65	29	16	7	9	4	223	0.42
Gchadi Bajana Section														
G1	5	3	30	18	65	43	45	28	12	7	3	1	160	0.39
G2	12	6	49	25	65	34	56	28	11	5	4	2	197	0.38
G3	6	2	62	21	94	31	116	39	10	6	3	1	301	0.36
G4	5	1	86	24	126	36	115	33	14	4	7	2	353	0.36
G5	6	3	37	18	80	38	62	29	16	7	10	6	211	0.42
Bansi Paharpur Section														
BP1	3	2	16	9	75	44	60	35	12	7	6	3	172	0.43
BP2	6	3	20	9	90	44	80	37	12	5	5	2.	214	0.41
BP3	6	3	12	6	90	46	70	34	15	7	9	4	202	0.52
BP4	7	4	20	12	70	44	50	30	12	7	5	3	164	0.42
BP5	6	3	15	8	80	47	60	35	9	5	3	2	173	0.41

BP6	4	2	17	8	90	43	80	38	15	7	5	2	211	0.43
BP7	3	2	10	5	90	45	70	35	20	10	7	3	200	0.45
BP8	5	3	7	9	80	43	60	32	15	8	9	5	186	0.44
BP9	10	4	20	7	110	41	90	33	25	9	15	6	270	0.44
BP10	5	2	10	5	90	43	70	34	20	10	12	6	207	0.46
BP11	7	3	15	6	105	40	95	37	25	9	13	5	260	0.46
BP12	4	2	11	5	90	47	70	35	15	7	9	4	199	0.44
BP13	5	3	20	11	80	44	60	33	10	6	5	3	180	0.43
Rudawal Section														
RD1	3	1	22	7	128	45	102	35	24	8	12	4	291	0.44
RD2	7	3	62	24	92	36	81	31	14	5	3	1	259	0.36
RD3	6	2	59	21	100	36	89	34	19	6	4	1	277	0.41
RD4	5	2	40	15	97	39	69	26	31	11	18	7	260	0.45
RD5	7	4	36	20	65	37	46	26	14	11	5	2	173	0.41
RD6	4	1	53	17	115	38	90	29	29	9	18	6	309	0.44
RD7	6	3	27	13	82	41	61	30	18	9	6	4	200	0.42
RD8	5	2	42	14	107	37	87	30	40	14	6	3	287	0.44
RD9	7	4	30	18	72	40	50	27	16	8	5	3	180	0.41
RD10	5	3	30	17	77	43	54	30	7	4	4	3	177	0.40
Average Area Level		3		10		39		34		10		4		0.44

Table 4. Sphericity of detrital grains of the Upper Bhander Sandstone in parts of Uttar Pradesh - Rajasthan States.

Sample No.	Low Sphericity (<0.3)		Medium Sphericity (0.6)		High Sphericity (>0.9)		Total Grains	Mean Sphericity
	N	%	N	%	N	%		
Rasulpur Section								
R1	22	54	11	36	4	10	37	0.52
R2	125	44	113	40	46	16	284	0.51
R3	159	36	171	39	112	25	442	0.57
R4	209	50	142	34	68	16	419	0.50
R5	139	44	111	35	65	21	315	0.52
R6	120	41	110	38	60	21	290	0.53
R7	97	37	116	44	59	19	116	0.57
R8	127	42	131	43	44	15	302	0.52
R9	124	45	123	44	29	11	276	0.49
R10	60	49	35	33	19	18	114	0.49
R11	45	57	30	26	16	17	91	0.49
R12	42	38	47	43	21	19	110	0.53
R13	39	43	32	35	20	22	91	0.53
Tehra Section								
T-1	54	49	41	37	16	14	111	0.49
T-3	54	48	43	38	15	14	112	0.49
T-5	77	53	54	37	14	10	145	0.46
T-6	46	60	26	34	5	6	77	0.44
T-7	28	57	16	33	5	10	49	0.45
T-8	36	54	24	36	7	10	67	0.46
T-9	26	60	13	31	4	9	43	0.44
T-10	23	49	17	36	7	15	47	0.50
T-11	24	40	25	42	11	18	60	0.53
T-12	73	55	44	34	14	11	131	0.46
T-13	30	51	20	34	9	15	59	0.49
T-14	24	53	14	31	7	16	45	0.49
Bakoli Section								
B1	73	56	44	33	14	11	131	0.46
B2	78	45	62	36	33	19	173	0.53
B3	55	48	40	35	20	17	115	0.15
B4	50	47	42	40	14	13	106	0.50
B5	48	56	29	34	8	10	85	0.45
Rupbas Section								
RP1	52	53	32	33	14	19	98	0.48
RP2	79	55	63	25	33	20	175	0.53
RP3	88	48	64	36	30	16	182	0.51
RP4	79	45	63	36	33	19	175	0.53
RP5	52	53	32	33	14	14	98	0.48
RP6	87	51	58	34	24	15	169	0.49
Gatouli Section								
GH1	94	50	66	35	28	15	188	0.49
GH2	43	44	35	36	19	20	97	0.52
GH3	58	55	43	25	16	20	117	0.49
GH4	43	50	35	37	19	13	97	0.52
GH5	36	49	26	35	12	16	74	0.49
GH6	35	44	29	37	15	19	79	0.52

Mewali Section								
M1	49	53	30	32	14	15	93	0.43
M2	26	44	23	39	10	17	59	0.51
M3	69	51	49	36	18	13	136	0.49
M4	45	48	35	38	13	14	93	0.48
M5	39	48	29	36	13	16	81	0.49
M6	37	50	25	34	12	16	74	0.49
M7	42	57	22	30	10	13	74	0.47
Jagnair Section								
J1	36	46	28	35	15	19	79	0.52
J2	92	51	58	32	29	16	179	0.48
J3	32	49	22	34	11	17	65	0.50
J4	22	46	18	38	8	16	48	0.52
J5	33	62	13	25	7	13	53	0.45
J7	40	49	28	35	13	16	81	0.50
Holipura Section								
HP1	72	44	61	37	31	19	164	0.52
HP2	23	48	20	42	5	10	48	0.48
HP3	52	50	36	34	17	16	105	0.50
Tantpur Section								
TT1	86	49	60	34	30	17	176	0.50
TT2	109	46	88	37	38	16	235	0.50
TT3	49	56	29	33	10	11	88	0.46
TT4	35	56	20	32	7	11	62	0.46
TT5	55	43	53	41	20	16	128	0.52
TT6	51	46	36	32	25	22	112	0.52
TT7	83	47	72	41	20	11	175	0.49
TT8	51	47	40	37	17	16	108	0.50
Baretha Section								
BD1	101	59	55	32	15	9	171	0.43
BD2	126	64	50	26	19	10	195	0.42
BD3	220	68	85	26	18	6	323	0.40
BD4	176	69	60	23	20	8	256	0.41
BD5	150	70	50	24	12	6	212	0.40
BD6	120	71	55	22	11	7	186	0.41
BD7	92	65	49	30	18	5	159	0.45
BD8	120	58	55	31	11	11	186	0.41
BD9	180	72	56	22	13	6	249	0.38
BD10	170	78	35	16	12	6	217	0.36
BD11	155	66	63	27	16	7	234	0.41
Gchadi Bajana Section								
G1	170	64	57	22	37	14	264	0.45
G2	157	63	76	30	17	7	250	0.42
G3	159	57	88	32	31	11	278	0.46
G4	261	50	187	36	71	14	519	0.48
G5	345	53	208	32	98	15	651	0.48
Bansi Paharpur Section								
BP1	94	55	59	34	18	11	171	0.45
BP2	61	51	42	35	17	14	120	0.48
BP3	58	50	41	35	7	15	116	0.50
BP4	55	54	33	33	13	13	101	0.46
BP5	64	54	41	34	14	12	119	0.46
BP6	56	48	42	36	19	16	117	0.49
BP7	56	49	43	37	16	14	115	0.48

BP8	50	55	27	30	13	15	90	0.47
BP9	94	49	72	37	27	14	193	0.48
BP10	96	54	62	35	19	11	177	0.46
BP11	94	51	70	38	21	11	185	0.47
BP12	67	50	52	38	16	12	135	0.49
BP13	30	46	27	42	8	12	65	0.50
Rudawal Section								
RD1	37	50	25	34	12	16	74	0.49
RD2	66	63	25	24	13	13	104	0.49
RD3	23	59	10	26	6	15	39	0.45
RD4	37	51	24	33	12	16	73	0.49
RD5	23	66	8	23	4	11	35	0.42
RD6	32	55	15	26	11	19	58	0.48
RD7	48	56	24	29	13	15	85	0.47
RD8	10	59	4	23	3	18	17	0.46
RD9	37	51	23	32	12	17	72	0.49
RD10	64	60	29	27	14	13	107	0.44
Average Area Level		52		33		15		0.47

action is either weak or deposition is very rapid so that sediments do not have a chance to be subjected to input of any mechanical energy after deposition. Whereas the supermature sediments are subjected to intense abrasion and sorting in high energy environments such as beaches or desert dunes. The studied sandstone samples are mostly texturally mature (63 samples), 28 samples are submature and 14 samples are supermature (Table 5).

BIVARIANT PLOT OF TEXTURAL PARAMETERS

Bivariant plots are used to show the interrelationship of various textural attributes of the Upper Bhander Sandstone. Different textural parameters of sandstones are plotted against each other and their relationship is determined statistically by computing their correlation coefficient values. Different plots which are used include mean size versus sorting, mean size versus roundness, mean size versus sphericity, roundness versus sorting and sphericity versus sorting.

Mean size versus sorting

The mean size of the studied samples plotted against their sorting and the correlation coefficient value of – 0.239 shows weak inverse relationship between size and sorting (Figure 16A). The mean size of the grains decreases with increase in sorting.

Mean size versus roundness

The mean size versus roundness plot shows an inverse relationship with their correlation coefficient value of - 0.141. Inverse relationship suggests that decrease in size is accompanied by decrease in roundness of grains (Figure 16B).

Table 5. Textural Parameters of detrital grains of the Upper Bhander Sandstone in parts of Uttar Pradesh - Rajasthan States.

Sample No.	Mean Size(Φ)		Sorting(Φ)		Mean Roundness of Grains		Maturity
Rasulpur Section							
R1	2.33	Medium grained	0.75	Moderately sorted	0.43	Subrounded	Mature
R2	2.45	Medium grained	1.15	Poorly sorted	0.44	Subrounded	Mature
R3	1.25	Medium grained	0.72	Moderately sorted	0.53	Rounded	Super mature
R4	2.1	Medium grained	1.09	Poorly sorted	0.45	Subrounded	Mature
R5	2.26	Medium grained	1.09	Poorly sorted	0.39	Subrounded	Super mature
R6	2.5	Medium grained	1.26	Poorly sorted	0.42	Subrounded	Mature
R7	1.6	Medium grained	0.83	Moderately sorted	0.48	Subrounded	Mature
R8	1.7	Medium grained	1	Moderately sorted	0.45	Subrounded	Mature
R9	1.93	Medium grained	0.95	Moderately sorted	0.49	Subrounded	Sub mature
R10	2.64	Medium grained	1.22	Poorly sorted	0.43	Subrounded	Sub mature
R11	2.65	Medium grained	1.14	Poorly sorted	0.47	Subrounded	Mature
R12	2.33	Medium grained	1.35	Poorly sorted	0.45	Subrounded	Mature
R13	1.75	Medium grained	0.83	Moderately sorted	0.49	Subrounded	Mature
Tehra Section							
T-1	2.48	Medium grained	1.07	Poorly sorted	0.37	Subrounded	Mature
T-3	2.3	Medium grained	0.73	Moderately sorted	0.42	Subrounded	Mature
T-5	1.15	Medium grained	0.87	Moderately sorted	0.43	Subrounded	Super mature
T-6	3.16	Fine grained	0.89	Moderately sorted	0.46	Subrounded	Mature
T-7	1.15	Medium grained	1.05	Poorly sorted	0.50	Rounded	Mature

T-8	2.36	Medium grained	0.90	Moderately sorted	0.44	Subrounded	Sub mature
T-9	1.35	Medium grained	0.90	Moderately sorted	0.46	Subrounded	Mature
T-10	1.36	Medium grained	1.04	Poorly sorted	0.46	Subrounded	Sub mature
T-11	1.38	Medium grained	0.97	Moderately sorted	0.48	Subrounded	Mature
T-12	2.56	Medium grained	1.16	Poorly sorted	0.47	Subrounded	Sub mature
T-13	1.36	Medium grained	0.94	Moderately sorted	0.50		Mature
T-14	1.46	Medium grained	0.80	Moderately sorted	0.45	Subrounded	Mature
Bakoli Section							
B1	2.3	Medium grained	0.91	Moderately sorted	0.45	Subrounded	Sub mature
B2	2.68	Medium grained	1.02	Poorly sorted	0.41	Subrounded	Mature
B3	2.58	Medium grained	1.14	Poorly sorted	0.44	Subrounded	Mature
B4	2.45	Medium grained	0.73	Moderately sorted	0.51	Rounded	Mature
B5	2.2	Medium grained	0.89	Moderately sorted	0.45	Subrounded	Mature
Rupbas Section							
RP1	3.05	Fine grained	0.96	Moderately sorted	0.43	Subrounded	Mature
RP2	2.76	Medium grained	0.89	Moderately sorted	0.45	Subrounded	Mature
RP3	2.73	Medium grained	0.69	Moderately Well sorted	0.45	Subrounded	Mature
RP4	2.74	Medium grained	0.96	Moderately sorted	0.43	Subrounded	Mature
RP5	2.76	Medium grained	0.89	Moderately sorted	0.45	Subrounded	Mature
RP6	2.73	Medium grained	0.69	Moderately Well sorted	0.45	Subrounded	Mature
Gatouli Section							
GH1	2.18	Medium grained	0.78	Moderately sorted	0.44	Subrounded	Mature
GH2	1.58	Medium grained	0.87	Moderately sorted	0.47	Subrounded	Mature

GH3	1.81	Medium grained	0.71	Moderately Well sorted	0.44	Subrounded	Mature
GH4	2.11	Medium grained	0.86	Moderately sorted	0.40	Subrounded	Sub mature
GH5	2.06	Medium grained	0.62	Moderately Well sorted	0.46	Subrounded	Sub mature
GH6	1.56	Medium grained	0.89	Moderately sorted	0.47	Subrounded	Mature
Mewali Section							
M1	2.25	Medium grained	0.93	Moderately sorted	0.42	Subrounded	Sub mature
M2	2.43	Medium grained	0.76	Moderately sorted	1.12	Well Rounded	Mature
M3	2.66	Medium grained	0.90	Moderately sorted	0.44	Subrounded	Sub mature
M4	2.26	Medium grained	0.82	Moderately sorted	0.46	Subrounded	Sub mature
M5	2.25	Medium grained	1	Moderately sorted	0.46	Subrounded	Sub mature
M6	1.73	Medium grained	0.79	Moderately sorted	0.44	Subrounded	Mature
M7	1.7	Medium grained	0.83	Moderately sorted	0.46	Subrounded	Mature
Jagnair Section							
J1	1.98	Medium grained	0.69	Moderately Well sorted	0.44	Subrounded	Super mature
J2	2.98	Medium grained	0.82	Moderately sorted	0.42	Subrounded	Mature
J3	1.73	Medium grained	0.71	Moderately Well sorted	0.44	Subrounded	Super mature
J4	1.36	Medium grained	0.74	Moderately sorted	0.45	Subrounded	Mature
J5	1.16	Medium grained	0.71	Moderately Well sorted	0.46	Subrounded	Mature
J7	2.1	Medium grained	0.66	Moderately Well sorted	0.44	Subrounded	Mature
Holipura Section							
HP1	3.35	Medium grained	0.92	Moderately sorted	0.45	Subrounded	Mature
HP2	2.71	Medium grained	0.92	Moderately sorted	0.46	Subrounded	Sub mature

HP3	2.8	Medium grained	1.02	Poorly sorted	0.47	Subrounded	Sub mature
Tantpur Section							
TT1	3.5	Fine grained	0.83	Moderately sorted	0.41	Subrounded	Mature
TT2	2.8	Medium grained	0.49	Well sorted	0.42	Subrounded	Mature
TT3	3.45	Fine grained	0.76	Moderately sorted	0.42	Subrounded	Sub mature
TT4	3.3	Fine grained	0.77	Moderately sorted	0.45	Subrounded	Sub mature
TT5	2.78	Medium grained	0.76	Moderately sorted	0.43	Subrounded	Mature
TT6	2.91	Medium grained	0.94	Moderately sorted	0.44	Subrounded	Sub mature
TT7	2.68	Medium grained	1.02	Poorly sorted	0.41	Subrounded	Mature
TT8	2.93	Medium grained	0.85	Moderately sorted	0.42	Subrounded	Mature
Baretha Section							
BD1	2.76	Medium grained	0.49	Well sorted	0.51	Rounded	Mature
BD2	2.91	Medium grained	0.59	Moderately Well sorted	0.42	Subrounded	Mature
BD3	3.30	Fine grained	0.72	Moderately sorted	0.43	Subrounded	Mature
BD4	2.75	Medium grained	0.64	Moderately Well sorted	0.42	Subrounded	Mature
BD5	4.48	Fine grained	0.51	Moderately Well sorted	0.38	Subrounded	Sub mature
BD6	3.03	Fine grained	0.62	Moderately Well sorted	0.38	Subrounded	Sub mature
BD7	3.1	Fine grained	0.68	Moderately Well sorted	0.43	Subrounded	Mature
BD8	2.98	Medium grained	0.80	Moderately sorted	0.39	Subrounded	Sub mature
BD9	3.31	Fine grained	0.62	Moderately Well sorted	0.40	Subrounded	Sub mature
BD10	3.05	Fine grained	0.59	Moderately Well sorted	0.42	Subrounded	Mature
BD11	2.4	Medium grained	0.75	Moderately sorted	0.40	Subrounded	Mature
Gchadi Bajana Section							
G1	3.1	Fine grained	0.63	Moderately Well sorted	0.39	Subrounded	Mature
G2	3.16	Fine grained	0.65	Moderately Well sorted	0.38	Subrounded	Mature
G3	2.98	Medium grained	0.61	Moderately Well sorted	0.36	Subrounded	Mature

G4	2.9	Medium grained	0.59	Moderately Well sorted	0.36	Subrounded	Super mature
G5	2.96	Medium grained	0.67	Moderately Well sorted	0.42	Subrounded	Mature
Bansi Paharpur Section							
BP1	3.08	Fine grained	0.77	Moderately sorted	0.43	Subrounded	Mature
BP2	3.16	Fine grained	0.60	Moderately Well sorted	0.41	Subrounded	Mature
BP3	3.28	Fine grained	0.75	Moderately sorted	0.52	Rounded	Sub mature
BP4	2.98	Medium grained	0.75	Moderately sorted	0.42	Subrounded	Mature
BP5	3.2	Fine grained	0.75	Moderately sorted	0.41	Subrounded	Sub mature
BP6	3.23	Fine grained	0.60	Moderately Well sorted	0.43	Subrounded	Sub mature
BP7	2.65	Medium grained	0.71	Moderately sorted	0.45	Subrounded	Mature
BP8	2.75	Medium grained	0.72	Moderately sorted	0.44	Subrounded	Mature
BP9	2.98	Medium grained	0.68	Moderately Well sorted	0.44	Subrounded	Mature
BP10	2.88	Medium grained	0.73	Moderately sorted	0.46	Subrounded	Mature
BP11	3.5	Fine grained	0.70	Moderately Well sorted	0.46	Subrounded	Sub mature
BP12	4.52	Fine grained	0.52	Moderately Well sorted	0.44	Subrounded	Sub mature
BP13	3.36	Fine grained	0.72	Moderately sorted	0.43	Subrounded	Sub mature
Rudawal Section							
RD1	1.48	Medium grained	0.67	Moderately Well sorted	0.44	Subrounded	Super mature
RD2	1.91	Medium grained	0.75	Moderately sorted	0.36	Subrounded	Super mature
RD3 .	1.78	Medium grained	0.84	Moderately sorted	0.41	Subrounded	Mature
RD4	1.6	Medium grained	0.69	Moderately Well sorted	0.45	Subrounded	Super mature
RD5	2.23	Medium grained	0.82	Moderately sorted	0.41	Subrounded	Super mature
RD6	1.56	Medium grained	0.72	Moderately sorted	0.44	Subrounded	Super mature
RD7	2.1	Medium grained	0.90	Moderately sorted	0.42	Subrounded	Super mature

RD8	1.58	Medium grained	0.69	Moderately Well sorted	0.44	Subrounded	Mature
RD9	1.76	Medium grained	0.69	Moderately Well sorted	0.41	Subrounded	Super mature
RD10	1.35	Medium grained	0.60	Moderately Well sorted	0.40	Subrounded	Super mature
Average Area Level	2.45		0.81		0.44		

Mean size versus sphericity

The mean size versus sphericity plot shows an inverse relationship with their correlation coefficient value of - 0.236 which states that the sphericity of the grains decreases as their size decreases (Figure 16C).

Roundness versus sorting

The Bivariant plot of roundness versus sorting has a correlation coefficient value of 0.061 which shows a weak relationship between sorting and roundness. The sorting of the grains decreases as their roundness decreases (Figure 17A).

Sphericity versus sorting

Sphericity is plotted against sorting and the correlation coefficient value for the plot 0.160 shows a weak relationship between sorting and sphericity. Sorting of the grains decreases as their sphericity decreases (Figure 17B).

BIMODALITY

The studied Upper Bhander Sandstone show bimodality, large rounded to sub rounded grains surrounded by small grains. Bimodality may be found in both eolian and beach environment. In eolian environment it is characterised of deflationary desert flats (Folk, 1980). In beach environment bimodality can occur in lower foreshore (backwash breaker zone) and probably in storm deposit layers (Taira and Scholle, 1979). The backwash breaker zone is characterised by concentration of coarse sediments. These coarse sediments may intermingle with "normal" beach sand by the following processes (Taira and Scholle, 1979).

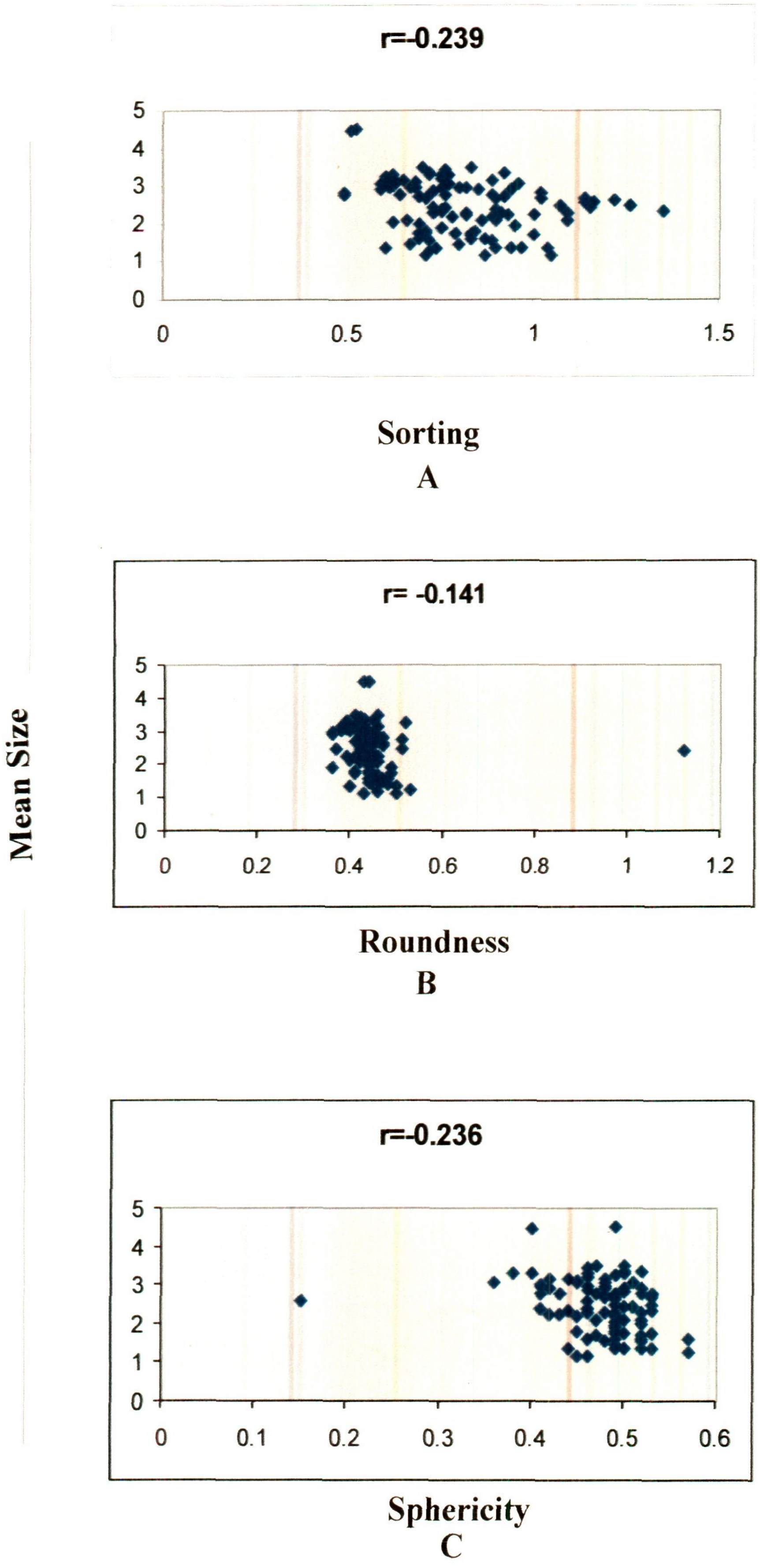
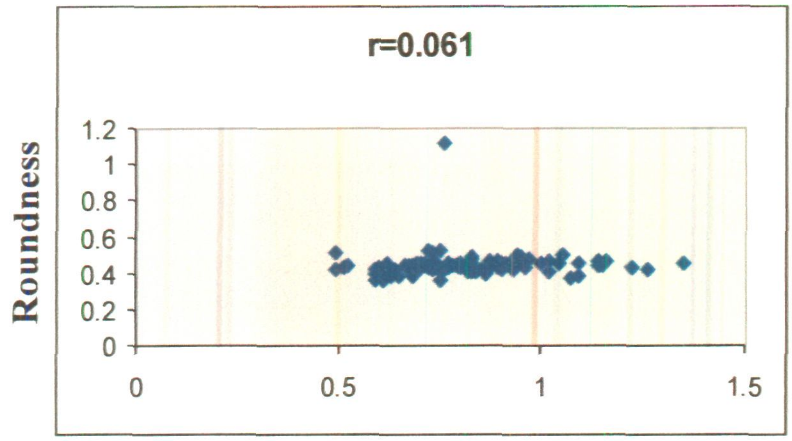
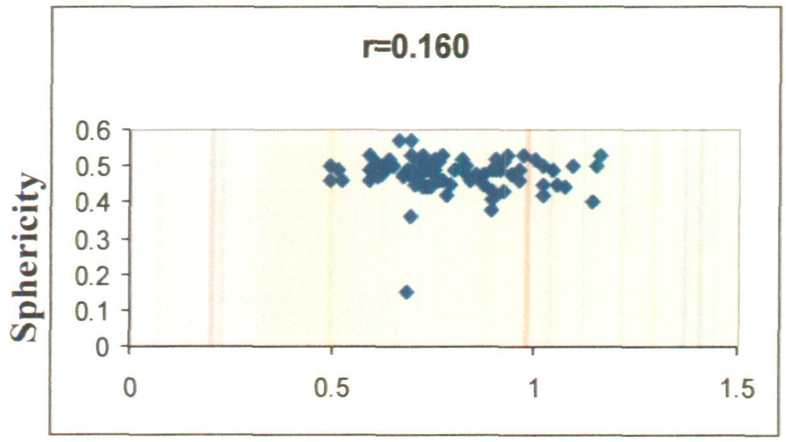


Figure 16.(A) Bivariant plots of mean size versus sorting, (B) roundness and (C) sphericity.



Sorting

A



Sorting

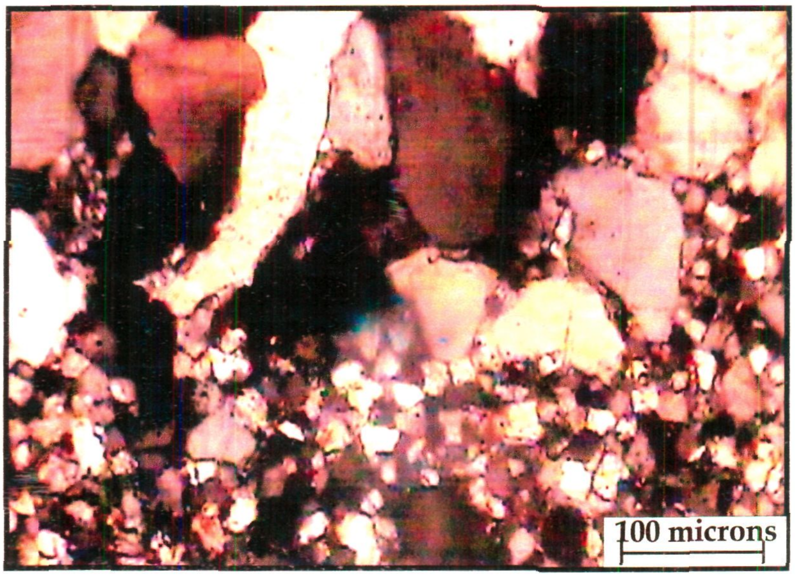
B

Figure 17.(A) Bivariant plots showing roundness versus sorting and (B) sphericity versus sorting.

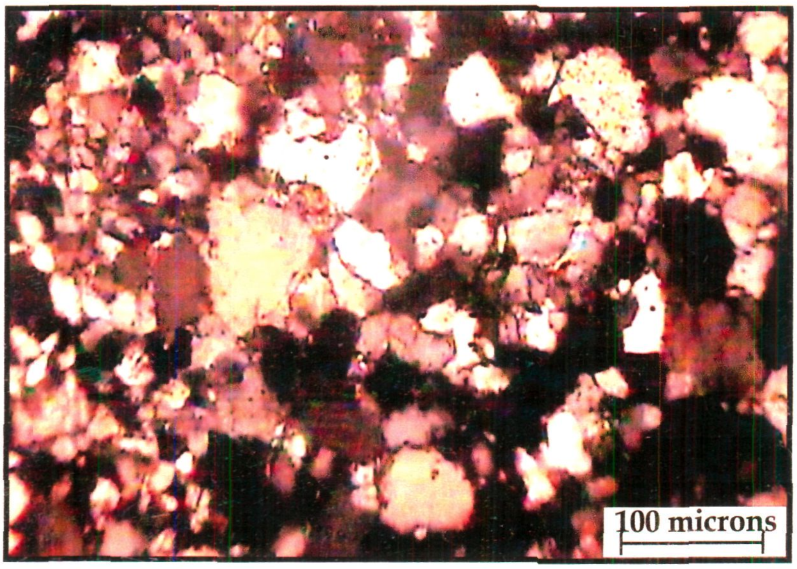
(a) dispersal of coarse fraction along the shoreline by longshore currents; (b) shore water migration of coarse fraction due to shoreward wind variation of bottom current velocity induced by shoaling waves, and (c) sea-ward transportation of coarse fraction by backwash.

Blatt (1992) discuss that abundance of bottom feeding organisms in shallow marine environment can give rise to bimodality by mixing of two well sorted laminae. Fraser (1976) associated presence of bimodality (Starved Rock Member, Upper Mississippi Valley) to burrowing activity and supposes its formation by the mixing action of burrowing organisms. Clifton (1983) showed that in back wash surface creep (backwash bed flow); coarse grained fraction is transported to backwash breaker zone. During storms on high wave energy coarse grained fraction is carried from lower shoreface (backwash breaker zone) to upper foreshore and backshore. The storm deposit layer thus formed may acquire bimodality due to mixing of coarse and normal beach sand fractions.

The studied Upper Bhander Sandstone shows moderately to moderately well sorted and coarse layer overlain by a fine layer showing bimodality (Plate IV A,B). Bimodality in the sandstones reflects that theses sediments were deposited in beach shoal environment. More evidence of beach/ shoal environment is discussed in the chapter on depositional environment.



A



B

PLATE IV

A, B. Photomicrograph showing bimodality of detrital grains in the Upper Bhander Sandstone in the form of coarser and finer layers.

CHAPTER IV

FACIES ANALYSIS

INTRODUCTION

The term facies represents a body of rock with specified characteristics. It can be handled at outcrop or from boreholes and thus defined on the basis of color, bedding, composition, texture, fossil and sedimentary structures (Reading, 1986). In the present study, the term 'Facies' has been employed in an interpretive sense following the reconstruction of ancient depositional processes and environments in different localities. The interpretation of facies is based on the study of their spatial relationship and internal characteristics (lithology and sedimentary structures etc.) and comparing this information with the knowledge gained from modern sedimentary environments and well studied stratigraphic units. Subdivision of a rock sequence into constituent facies (or units of similar aspect) is essentially a classification procedure and the degree of subdivision is basically governed by the objectives of the study.

A detailed study of the sedimentary facies gives us idea about the depositional environments and basin fill processes during the initial stage of the basin formation. The present work reveals the results of the lithofacies and their correlation among the sections based on facies assemblages, to decipher sedimentary processes and depositional environment. For this purpose, various sedimentary signatures of the rocks were recorded from different sections. Most of the physical parameters such as bedding, nature of contacts between beds, sedimentary textures and related small-scale structures, as well as

In addition, lateral and vertical facies relationship and three-dimensional geometry of depositional units were recorded.

The Upper Bhander Sandstone show variable thickness of individual beds as indicated by the measured stratigraphic sections. Thirteen stratigraphic sections were measured for vertical and lateral facies variation across the ridges, road cuts and river valleys at different outcrops over a stretch of about 70km from west to east [1. Baretha, 2. Gchadi Bajana, 3. Rudawal, 4. Holipura, 5. Tantpur, 6. Mewali, 7. Bansi Paharpur, 8. Jagnair, 9. Rupbas, 10. Gatouli, 11. Bakoli, 12. Tehra, 13. Rasulpur] (Figure 18). Nine facies that constitutes the Upper Bhander Sandstone are described as follows:

a) **Tabular cross-bedded sandstone facies (Sp):** This facies is common in all of the measured sections. Best exposure of this facies was observed at Baretha section where it attains the maximum thickness (7.7m) (Plate II B, C) .This facies is fine to medium grained, moderately to moderately well sorted, pinkish to white in color. Cross-beds are both in co-sets and in single sets. Each foreset ranges in thickness from 1cm-6cm.The facies at places is bounded by gently erosional reactivation surfaces. Small-scale, low-angle tabular cross-bedded sandstones are also observed in the measured sections with the maximum thickness 0.1 to 1m.Herringbone cross bedding was also seen associated with tabular cross bedded sandstone in 5 measured sections (Rudawal, 7.9-8.9m, Bansi Paharpur, 0-2.0m, Baretha, 17.3-24.9m, Mewali, 6.2-7.7m and Tehra, 12.9-13.9m).

b) **Trough cross-bedded sandstone facies (St):** Out of 13 measured sections this facies is present in 10 sections and the best exposure of this facies is seen in Tehra section where it attains the maximum thickness of about 3m (Plate IIA). This facies comprises medium to fine grained, moderately well sorted to well sorted, red, white and yellow colored,

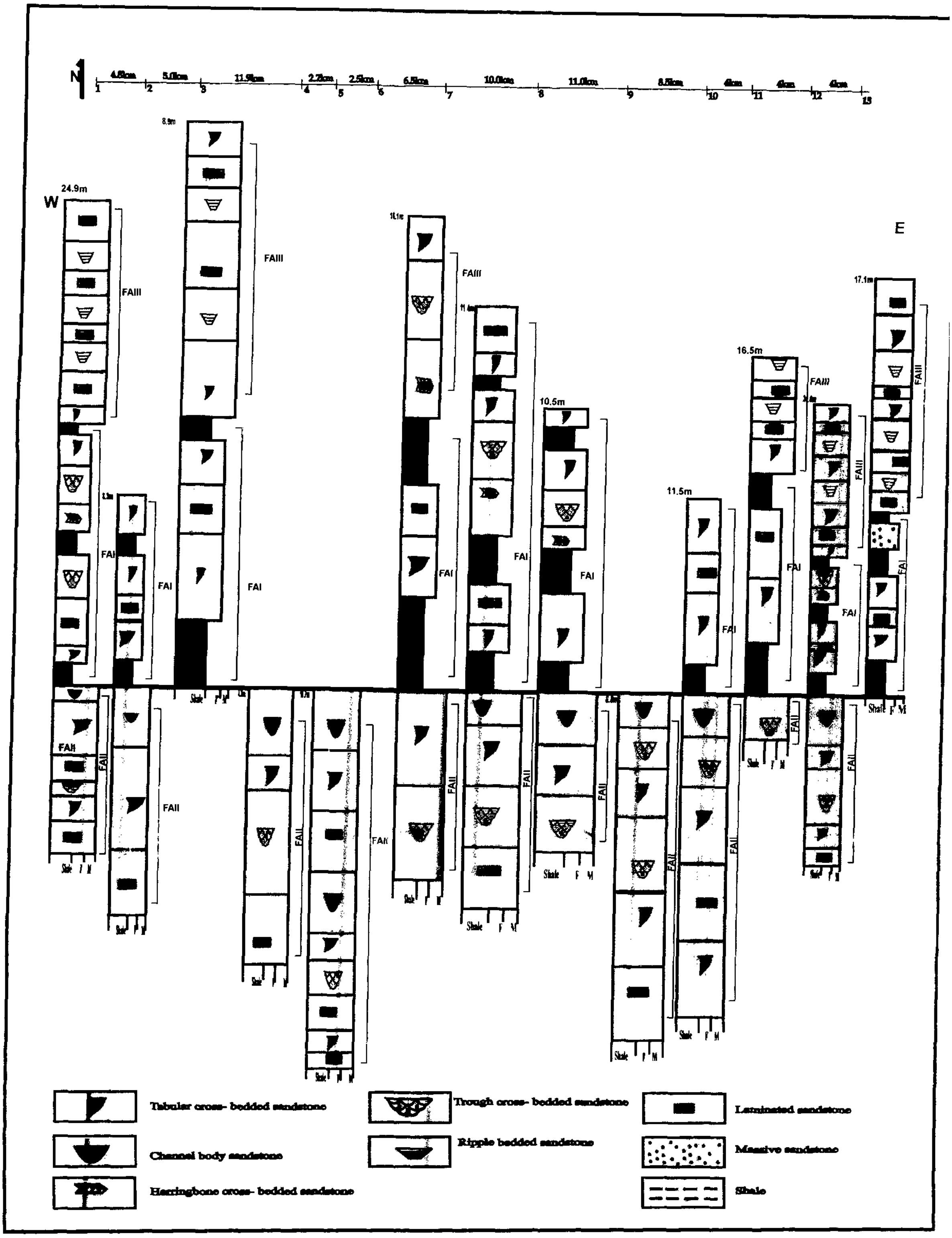


Figure 18. Lateral and Vertical variation of the thirteen lithostratigraphic sections of the Upper Bhander Sandstone in parts of Uttar Pradesh-Rajasthan States.

trough cross-bedded sandstone. The sandstone beds are thick to thin. Trough cross-bedded units are occasionally distorted, swaley-type in at places. The foresets are truncated tangentially at the lower bounding surface. The curvilinear foresets run parallel to the basal scoured surface. At places, traces of foreset are commonly symmetrically curved.

c) **Massive sandstone facies (Sm):** This facies is present in each section but the best exposure is seen in Bakoli section where it attains the maximum thickness (3.0m). Massive sandstone facies occurs as thick units lacking visible sedimentary structures. This facies is reddish in color, medium to fine grained and moderately well sorted to well sorted.

d) **Interbedded shale and fine grained sandstone facies (Si-Fi):** This facies is present only in 2 sections (i.e., Tehra ,1m and Ghatouli, 1.4m).The sandstone is medium to fine grained, poorly sorted, white to dark red in color. The sandstone beds are thin and wavy and exhibit parallel lamination, small-scale cross-bed and channel units. The shale bed is red in color and faintly laminated. The facies shows sharp to wavy contact with the upper massive sandstone facies .

e) **Parallel laminated sandstone facies (Sl):** This facies is common in 11 sections with the maximum thickness of 3m in Tehra section (Plate IC). The sandstone is medium grained, light pink to white colored, moderately sorted to moderately well sorted. The beds are planar laminated and exhibit low-angle cross-bedding. The bed contacts are sharp.

f) **Ripple laminated sandstone facies (Sr):** This facies is present in seven sections of the studied area. The maximum thickness of this facies is 1.5m in Bakoli section. The sandstone is medium to fine grained, reddish to pinkish colored, moderately well sorted to well sorted. Long round crested asymmetrical ripples as well as long crested wave generated symmetrical ripples are present (Plate IA,B). The wavelength of symmetrical ripples is 1-5cm and that of asymmetrical ripples is 2-7cm.

g) **Shale facies (Fi):** This facies occur only in 7 sections with the maximum thickness of 1.6m in Tehra section (Plate IIIA). The shale is fine grained, thinly bedded and tan colored. Desiccation cracks are present. The bed contacts are sharp and gradational.

h) **Channel sandstone facies (Sch):** This facies is present in 6 sections and the best exposure is seen at Tantpur section where it attains the maximum thickness of 6cm (Plate IIIC). This facies is fine to medium grained, moderately well sorted to well sorted, white and pink colored. Internally these sand bodies display cross and planar sets. The channel sandstone units are biconvex and occur as isolated or laterally coalescent bodies or are arranged enechelon. The northerly orientation of the channel axis closely coincides with the strike of cross foresets and is diagonal to the regional paleoflow direction as inferred from the associated cross bedded sandstone facies.

i) **Herringbone cross-bedded sandstone facies (Shb):** This facies is present in 5 sections and the best exposure is seen at Bansi Paharpur section where the thickness of cross bed sets varies from 2-3cm (Plate IIIB). This facies is mostly fine to medium grained, thick to thin bedded, moderately to moderately well sorted and reddish in color. The herringbone cross beds are mostly associated with laminated, trough and planar cross bed sets.

PALAEOCURRENT ANALYSIS

Palaeocurrent data provide information on the direction of sediment transport in the geological past. The analysis of palaeocurrent attribute is a vital part of the study of the sedimentary rocks in the sense that it provides information on paleogeography, palaeoslope, current and wind directions and is quite useful in facies interpretation. The technique of palaeocurrent analysis has become a routine component of basin analysis as it gives information about the pattern of sediment dispersal and the depositional environment prevalent at that time besides the direction of regional palaeoslope.

In the present study palaeocurrent reconstructions are mainly based on large scale planar and trough-cross bedding. Ripple marks were observed occasionally in the study area and their palaeogeographic interpretation was not attempted in view of the deficient data. Palaeocurrent study was carried out in several stages which include:

- Measurement of cross bedding azimuths in the field
- Statistical analysis of azimuthal data and
- Interpretation of sediment dispersal patterns and palaeslopes.

METHODOLOGY

Most of the azimuthal data were collected from the cross bedded sandstones of the study area. A total of 433 cross-beddings azimuths were collected at 13 localities of the study area. For analyzing azimuthal data rose diagrams were constructed by grouping cross-bedding azimuths in 30° classes.

The variability analysis of cross-bedding azimuths involves the following steps:

1) Study of the patterns of rose diagrams; 2) Calculation of vector mean (Φv) and vector magnitude (L%) by vector summation of Curray (1956); and 3)

calculation of standard deviation (S) and variance (S^2) determined for distributions with 20° or more azimuths.

CONSISTENCY OF PALAEOFLOW AND PALAEOSLOPE THROUGH TIME

In order to determine the consistency of palaeocurrent pattern or lack of it from base to top in the Upper Bhander rocks, the foreset azimuthal data for trough and tabular cross bedding were analysed in each section, both graphically and statistically. The corresponding data on the vector means, vector magnitudes, variance and standard deviation and the pattern of the rose diagrams are listed in (Table 6) for each section (Figure 19). The section-wise details of the palaeocurrent study are described as under:

Rasulpur section

In the basal part of this section the tabular cross bedded facies is dominant and the azimuths show bimodal palaeocurrent pattern, with modes directed northeast (30°-60°) and south (180°-210°), vector mean 68° and vector magnitude 56% respectively. However, higher up in the section trough cross bedding becomes dominant with a trimodal palaeocurrent pattern directed southeast (120°-150°), west-south-west (240°-270°) and westerly (270°-300°) with vector mean 198°and vector magnitude 62% respectively.

Tehra section

In this section the tabular cross bedding show trimodal palaeocurrent pattern with modes directed towards easterly (90 °-120 °), north-north-west (330 °-360 °) and south-south-east (150 °-180 °), vector mean 305° and vector magnitude 42% respectively. However, the trough cross bedding show bimodal palaeocurrent pattern directed south (180 °-210 °) and southwest (210 °-240 °), vector mean 217 ° and vector magnitude 59% respectively.

Table 6. Patterns and statistical parameters of the variability of cross bedding azimuths (for both tabular and trough cross beds) and palaeoslope direction of the Upper Bhander sandstone in parts of Uttar Pradesh - Rajasthan States.

N= Number of azimuths; θv = Vector mean; L% = Vector magnitude;
S=Standard deviation; S^2=Variance and P- Palaeoslope.

Section	N	Rose pattern (both Trough & Tabular)	θv (degree)		L%		S		S^2		P
			Trough	Tabular	Trough	Tabular	Trough	Tabular	Trough	Tabular	
Rasulpur	45	Bimodal	198	68	62	56	71	96	4972	9167	
Tehra	50	Trimodal	217	305	59	42	63	102	3934	10335	
Bakoli	15	Unimodal	81	216	82	65	13	20	180	410	
Holipura	20	Bimodal	-	63	-	65	-	16	-	260	
Rupbas	24	Unimodal	-	152	-	69	-	99	-	9816	
Ghatouli	19	Trimodal	255	293	99	58	69	134	4773	18048	
Mewali	47	Trimodal	206	34	40	26	116	53	13449	2756	
Jagnair	34	Bimodal	351	60	82	51	79	46	6301	2161	
Tantpur	45	Trimodal	77	17	46	22	55	56	3074	3168	
Baretha	24	Trimodal	-	54	-	49	-	51	-	2599	
Gchadi bajana	28	Bimodal	-	216	-	61	-	96	-	9256	
Bansi Paharpur	24	Quadrimodal	221	218	87	41	11	102	129	10482	
Rudawal	36	Bimodal	150	249	71	53	121	66	14800	4356	
Area composite Level	403	Quadrimodal	133		47		87		6844		

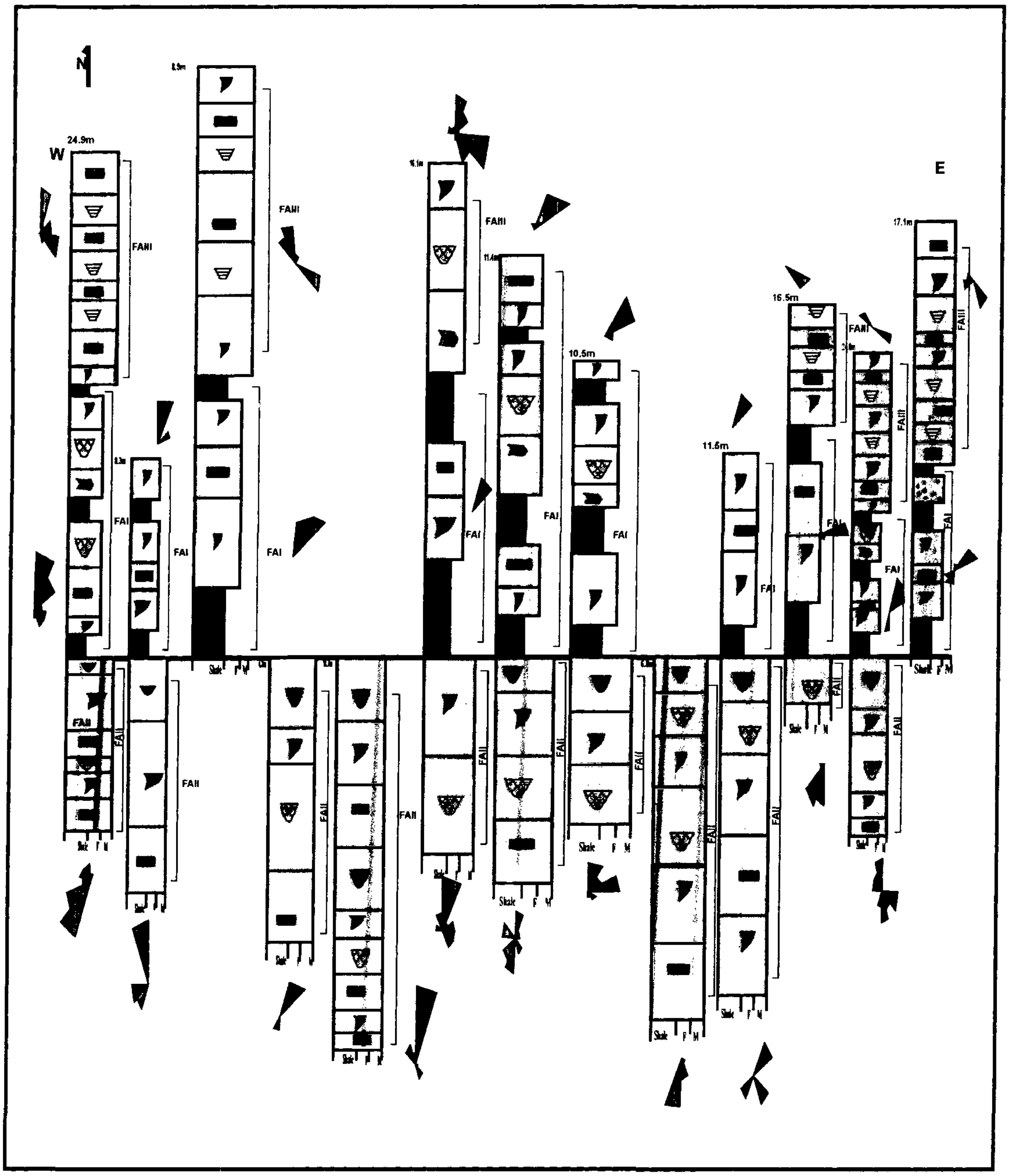


Figure 19. Palaeocurrent map of the Upper Bhander Sandstone in parts of Uttar Pradesh- Rajasthan states.

Bakoli section

The tabular cross bedding of this section show unimodal palaeocurrent pattern directed towards south west (210 °-240 °), vector mean 216 ° and vector magnitude 65% respectively. However, the trough cross bedding show bimodal palaeocurrent pattern directed towards east-north-east (60 °-90) and easterly (90 ° to120°),vector mean 81° and vector magnitude 82% respectively.

Holipura section

In this section, only tabular cross bedding is prominent showing bimodal palaeocurrent pattern, modes directed towards northeast (30°-60°) and easterly (90°-120°),vector mean 63 ° and vector magnitude 65% respectively.

Rupbas section

Like the above section, it is also having only tabular cross bedding showing unimodal palaeocurrent pattern, directed modes towards north-north-west (330°-360°), vector mean 152 ° and vector magnitude 69% respectively.

Ghatouli section

The tabular cross bedding shows trimodal palaeocurrent pattern with modes directed towards northeast (30 °-60 °), southeast (120 °-150 °) and southwest (210 °-240 °), vector mean 293 ° and vector magnitude 58% respectively. The trough cross bedding show unimodal palaeocurrent pattern, modes directed towards south-south-west (180 °-210 °), vector mean 255 ° and vector magnitude is 99% respectively.

Mewali

In this section both tabular and trough cross beddings show trimodal palaeocurrent pattern, modes directed northerly (0 °-30 °), east-north-east (60 °-90 °) and easterly (90 °-120 °), vector mean 34 ° and vector magnitude 26%. For trough cross bedding the modes directed easterly (90 °-120 °), southeast (120 °-150 °) and northeast (30 °-60 °), vector mean 206 ° and vector magnitude 40% respectively.

Jagnair section

The two types of cross bedding in this section show bimodal palaeocurrent pattern. For tabular cross bedding the modes are directed towards east-north-east (60 °-90 °) and northerly (0 °-30 °), vector mean 60 ° and vector magnitude 51%. Similarly for trough cross beds the modes are directed towards south - south –east (150 °-180 °) and southerly (180 °-210 °), vector mean 351 ° and vector magnitude 82 ° respectively.

Tantpur section

In this section tabular cross beds show trimodal palaeocurrent pattern, modes directed northerly (0 °-30 °), northwest (300 °-330 °) and northeast (30 °-60 °), vector mean 17 ° and vector magnitude 22% respectively.

Baretha section

Both the cross beddings of this section show trimodal palaeocurrent pattern, directed mode towards northerly (0 °-30 °),northeast (30 °-60 °) and easterly (90 °-120°),vector mean 54° and vector magnitude 49%. The trough cross-beds, shows the modes directed towards northerly (0 °-30 °), easterly (90 °-120 °) and northeast (60 °-90 °), vector mean 77 ° and vector magnitude 46% respectively.

Gchadi bajana section

In this section, only tabular cross bedding is present and shows bimodal palaeocurrent pattern, modes directed north- north -west (330 ° - 360 °) and west-south–west (240 ° - 270 °), vector mean 216 ° and vector magnitude is 61% respectively.

Bansi Paharpur section

In this section, the tabular cross beds show quadrimodal palaeocurrent pattern, directed modes towards southerly (180 °-210 °), easterly (0 °-30 °), southwest (210 °-240 °) and westerly (270 °to300 °), vector mean 218 ° and vector magnitude 41%. The trough cross beds show the unimodal palaeocurrent pattern, directed modes towards southwest (210 ° - 240 °), vector mean 221 ° and vector magnitude 87% respectively.

Rudawal section

The tabular cross bed azimuths show a bimodal palaeocurrent pattern, modes directed southwest (210 °-240 °) and north-north –west (330 °-360 °), vector mean 249° and vector magnitude 53%. The trough cross bed azimuth show a unimodal palaeocurrent pattern, directed modes northwest (300 °-330 °), vector mean 150 ° and vector magnitude 71% respectively.

INTERPRETATION OF THE AREA LEVEL

From the above study it is clear that most of the cross bedding azimuths of both trough and tabular cross bed show polymodal as well as bimodal-bipolar pattern and display 90 ° or nearly 180 ° reversal of palaeocurrent pattern, generally from north west to south east. The vector mean for tabular and trough cross beds at various sections show a wide range of distribution ranging from 17 ° to 293 ° and averages 149.57 ° for tabular cross beds and 77° to 255°and averages 190.4 ° for trough cross beds. The area aggregate composite distribution for the Upper Bhander Sandstone is 133 °. The vector magnitude values ranges from 22% to 65% and averages 51.42% for tabular cross beds and 33% to 99% and averages 68.3% for trough cross beds. The area aggregate composite distribution is 47%. The standard deviation values range from 16 to 144 and averages 77.21 for tabular cross bed and for trough cross bed the value ranges from 11 to121 and averages 69.5. The area aggregate composite distribution is 87. The variance of the sections ranges from 410 to 20778 and averages 7399 for tabular cross bed and 129 to 14800, averages 6382 for trough cross beds. The area aggregate composite distribution is 6844 (Table 6).

The rose diagrams exhibit polymodal, bidirectional/ bimodal pattern at most outcrops in the western and eastern part. The modal axis and subsidiary modes are generally towards southeast, east, northeast and intermittently towards southwest and northwest, and locally southward and northward, with few reversals. The bidirectional, bipolar (herringbone) bed forms in the channel fill sequences have been attributed to seaward directed ebb tidal currents and landward flood tidal currents (Hayes and Boothroyd, 1969; Klein, 1970; Oomkens, 1974; Reading and Collinson. 1996).

The polymodal to bimodal-bipolar pattern of tabular and trough cross beds, lower value of vector magnitude (47%) and higher values of variance (7548) indicate large azimuthal dispersion perhaps due to diverse current system of coastal environment including tidal and longshore currents. The diagonally /opposite oriented modal

classes of the two types of cross beddings at various sections of the study area are genetically significant and may correspond to ebb tidal/foreshore directed towards east or southeast and backshore/flood tidal currents parallel to or across the shoreline towards west or northwest.

FACIES ASSEMBLAGES

Facies assemblages represent genetically related facies development in a depositional environment. They represent different type of depositional processes which frequently occur together in the same overall depositional environment. These facies assemblages are commonly cyclic in nature. In the study area three genetically distinct facies assemblages were recognised.

Facies Association I (FAI): Prograding high energy Estuarine facies

The FA1 facies association is characterized by tabular package of facies including tabular cross-bedded sandstones, herring-bone cross-bedded sandstone, trough cross-bedded sandstone, wave ripple-bedded sandstone, parallel laminated sandstone along with interbedded shale-thinly bedded fine grained sandstone facies. The sandstones are medium grained and moderately sorted. Herring-bone cross-sets are present in medium grained, hard and, moderately sorted sandstones. Parallel lamination is seen in thinly bedded medium to fine grained sandstones. Shale is finely laminated; fine grained sandstones exhibit wavy contacts. The FA1 facies association is found in sections 1, 2, 3, 6, 7, 8, 10, 11, 12 and 13 respectively.

This assemblage is internally characterized by an overall fining- and thinning-upward succession. Tabular geometry of the facies assemblage FA1 suggests deposition in a flat-lying area. Large-scale tabular cross-bedded sandstones are interpreted as inter-tidal flood ramps lateral accretion of tidal channel bars (e.g., Casshyap and Aslam, 1992; Casshyap et al., 2001; Bose et al., 1999; Allen and Leather, 2006, Banerjee and jeevankumar, 2007). Presence of small-scale cross-bedding in the assemblage with lamination, ripple marks etc. suggests mixed tidal flat depositional environment. (e.g., Reineck and Singh, 1980). Moderately sorted sandstones indicate that the sediments were subjected to prolonged reworking by wave and tidal currents. Ripple bedded sandstone facies represents shallow water sand flats in tidal settings. Flat and rounded tops of the ripple bedform reflect planning-off during tidal reversal (Klein, 1970). Undulation in ripple-crests implies a transition from low energy to high energy conditions. The wave- or current generated ripple beds are common in sandy tidal flats or relatively shallow tidal channel margin (Meyer et al., 1998).

The parallel laminated sandstone facies represents occasional storm events during the intervening periods of low sediment influx in the inter-tidal environment (Dalrymple, 1992; Bjorklund, 2005). Cross-bedsets associated with laminated bedsets suggest their deposition on beach-face environment under the influence of strong tidal and longshore inter-tidal environment (e.g., Khalifa et al., 2006).

The presence of herring-bone cross-beds reflects the bed load deposition by reversing tidal currents of equal bed shear intensity and bottom current velocities. Flow direction reversals are associated with both rising flood and falling ebb stage of tidal cycle and these reversals are generally bi-polar. Reading (1986) and Reineck & Singh (1980) attributed these sedimentary structures to near-shore tidal environment (barrier associated) deposits. Moore (1979) attributed this facies to inter-tidal and shallow sub-tidal environment. Reading (1986) attributed herring-bone type cross-bedding in sandstones as diagnostic feature of tidal currents.

The interbedded fine-grained sandstone and red shale facies indicate deposition in lower shoreface transition zone of the inter-tidal environment. The alteration of sandstone and shale with abundance of small scale wave and current formed structures suggest their deposition in low energy intertidal environment (e.g., Evans, 1965; Van Stratten, 1954; Corcoran et al, 1998). The intertidal environment is characterized by phases of high energy (cross-bedded sandstones) and low energy (shale) condition. The interbedding of shale reflects a transition from a wave-agitated shoreface-foreshore setting to below wave base depositional setting. Presence of lamination and absence of wave-generated structures in the shale facies suggests deposition in a quiet water environment below wave base (e.g., Mukhopadhyay and Chaudhuri, 2003; Banerjee et al., 2006).

Fining upward sequence of the facies assemblage suggests decrease in energy and sediment supply. Tidal flats developing under progradational conditions are characterized by a fining-upward succession, consisting of coarse sediments at the base and progressively finer sediments toward the top. Tidal flat deposits commonly overlie estuarine channel sediments (Allen, 1991), and occur along the whole estuary (Dalrymple et al, 1992). Intertidal environmental settings are very sensitive where wave action is moderate and continental input is small. The FAI is the manifestation of progradation of sediments derived from a marine sediment source and is interpreted as accreting deposits in the tidal-dominated estuaries or wave-dominated inner parts of estuaries.

Facies Association II (FAII): Tidal and ebb channel facies

This facies association comprises of large-scale trough cross-bedded sandstone, large-scale tabular cross-bedded sandstones, parallel-laminated sandstones, massive sandstone and channel sand bodies. Sandstones are medium to fine grained, mainly thinly-bedded and graded. Palaeocurrent direction of the tabular and trough cross-beds show bi-directional pattern. Reactivation surfaces are present within cross-sets of sandstones. The FAII facies association is found in sections 1, 2, 4, 5, 6, 7, 8, 9, 10, 11 and 12.

Large-scale trough cross-bedded sandstones are interpreted as lateral migration of sand dunes of the tidal channel bars. Large-scale tabular cross-bedded sandstones are the product of migration of large dunes in subtidal channel. Both trough and tabular cross-bedded sandstones were thought to be deposited in tidal dominated nearshore coastal environment. Reactivation surfaces are formed as the subordinate current erodes the lee-face of the dune formed by the preceding dominating current (e.g., Dalrymple, 1992).

Thin bedded nature of sandstones indicates tidally influenced environment (Casshyap et al., 2001). Alternation of thick-and-thin behavior of the beds also reflects influence of ebb and flood tidal current. The upward fining large-scale cross-bed sets are interpreted to represent bars in the tidal channel (e.g., Sultan and Bjorklund, 2006).

This facies association represents shallow channels characterized by episodic fluctuation in flow velocity and tidal influence (Ahmad, 1988). Axis of the channel is parallel to the main palaeocurrent direction. Assemblage of the channel sandstone facies with other lithofacies of tidal origin (e.g., Large-scale tabular cross-bedded sandstones) suggest that channel sandstones are tidal channel (inlet) deposits (Shukla and Pant, 1996). Tidal inlets are more or less permanent passages between barrier islands that allow tidal exchange between the open sea and the lagoons, bays, and tidal marshes behind the islands. Inlet channels are generally deepest between the tips of the islands and shallow into tidal deltas both lagoon- ward (flood delta) and seaward (ebb delta). In a typical channel deposit, sands are coarsest in the deeper part of the channel and characterized by mainly ebb-oriented, tabular, planar cross beds, with reactivation surfaces formed by flood-driven currents. Sands of the channel margin exhibit trough-shaped sets of cross strata formed by both ebb dunes and large foresets formed by the lateral migration of the spit.

Internal features that favor channel deposition under the influence of tidal currents include presence of reactivation surfaces within cross sets; oppositely dipping foresets giving rise to bidirectional palaeocurrent data; low-angle dipping cross-sets and thick-and-thin behavior of the sandstone beds. Generation of all these structures requires fluctuating current energy, in tidal settings.

In nearshore and offshore areas, in presence of a positive relief, tidal currents tend to be channelized into bidirectional currents. These bidirectional tidal currents almost always show some degree of asymmetry, in that the flow in one direction is stronger than the other during the tidal cycle. Tidal channel deposits between the ebb and flood-tidal delta cover relatively large areas, because the channels and the tidal inlets between the barrier islands frequently migrate parallel to the shoreline. Channel fills usually began at the erosional base with coarse lag deposits. These are overlain by large scale bi-directional tabular and trough cross-beds. On the top of this sequence bi-directional small- to medium-scale tabular and trough cross-beds and parallel and ripple lamination are formed. The facies having similar elements reflect tidal inlets deposition (ebb channels) in lower estuary and influenced by marine transgression towards the top.

Facies Association III (FAII): Foreshore - offshore facies

Facies association FA3 comprises symmetrical & asymmetrical ripple, interference ripple, tabular cross-beds and laminated facies. The FA3 facies association occurs in sections 1, 3, 11, 12 and 13.

Ripple bedded fine sandstone shows features indicating deposition under oscillatory currents of weaker strength (e.g., Chakraborty et al., 1999). Reineck and Singh (1980) reported symmetrical wave ripples from 4 m deep water of offshore region and asymmetrical wave ripples from 0 to 2 m deep water of backshore-shoreface zone of Gulf of Gaeta, Italy. Asymmetrical ripples are either the manifestation of moderately deep offshore water or of much shallower water within the range of backshore-shoreface environment. Abundant asymmetrical ripples with crests oriented parallel to current direction are also an upper shoreface feature (Reading, 1986). Symmetrical ripple marks with rounded crests reflect planning-off during tidal reversal. The facies suggests deposition in shoreface environment (e.g., Allen & Leather, 2006). Occurrences of interference ripples indicate a depositional setting of extremely shallow water regime of backshore-shoreface environment. Interference ripples indicate temporary emergence and a shallow depth of water over the bars (e.g., Mukhopadhyay & Chaudhuri, 2003).

Large-scale tabular cross-bedded sandstones indicate high energy combined-flow condition in a lower shoreface environment (e.g., Duke et al, 1991, Arnott, 1993). Small-scale tabular cross-bedding represent deposition in tidal sandsheet bars in upper shoreface. High angle trough cross-bedded sandstones oriented in current direction flowing parallel to the shore are product of upper shoreface deposited by longshore currents. Abundance of low angle trough cross-beds is indicative of storm-dominated deposition above fair-weather wave base in the mid-to-upper shoreface (e.g., Lackie and Walker, 1982; Plint, 1988; Chakraborty et al., 1999; Bose et al., 1988). The thick and massive bedded nature of the sandstone indicates that Sm facies was deposited in the middle shore face (e.g., Galloway and Hobday, 1983). The parallel laminated sandstone represents offshore transport of sand during storms on the shoreface (Cheel, 1991; Brenchly et.al., 1993; Allen & Leather, 2006). Evenly laminated sandstones are produced by heavy storms, which erode sand from upper part of the beach and transfer them into suspension in turbulent water where they are settled down (e.g., Reineck and Singh, 1980; Araby and Motalib, 1999).

ARCHITECTURE OF FACIES ASSOCIATIONS

The spatio-temporal facies associations combined with palaeocurrent data are the basic tools to reconstruct depositional environment of a basin. Our observations on the Upper Bhander Sandstone are summarized in Table 7. As discussed earlier the Upper Bhander Sandstone comprises nine facies which are temporally grouped into three distinct depositional setup within barrier island system.

The basal 20m of the measured section are fining upward quartzite arenite deposited in tidal channels interbedded with large-scale planar and trough cross-bedded sandstone, massive and laminated sandstone units. The bedforms within this facies association are typical of tidal channel and deposition show bimodal palaeocurrent distribution, with modes 180° apart (Klein, 1970). Each bedform show dominance of tide in one direction; an observation similar to the ones made by De Raaf and Boerson (1971); Terwindt (1971) and Van Beek and Koster (1972). The SE directed ebb tide has dominated the upper part of the unit and formed the complex low angle bar bedforms. Flood tidal bedforms characterised by planar cross- stratification tend to die out in the sections westwards and are prominent in sections towards the more open marine conditions in the east. The ebb-tide formed bedforms show a transition from tabular sets to the low angle complex sets is a function of fluctuating near bed tidal current velocities (e.g.,Terwindt, 1971) reflecting varying river discharge during the ebb-tide (e.g.,Boersma, 1969). This basal unit of the Upper Bhander Sandstone represents tidal inlet deposition with fluctuating energy conditions.

Table 7. Detailed description of the facies, facies assemblages, palaeocurrent directions and depositional environment of the Upper Bhander Sandstone in parts of Uttar Pradesh - Rajasthan States.

Facies	Description	Facies Assemblage	Palaeocurrent direction (Mean)	Present in Sections	Depositional Environment
Trough cross bedded Sandstone (Facies St)	Fine grained. Small scale cross beds and laminated	FA1 associated with Sl facies	(35°)	1 (Baretha). 2 (Gchadi-Bajana). 3 (Rudawal). 6 (Mewali). 7 (Bansi Paharpur). 8 (Jagnair). 10 (Gatouli). 11 (Bakoli). 12 (Tehra). 13 (Rasulpur).	Prograding high energy Estuarine (back barrier)
Tabular cross-bedded sandstone (Facies Sp)	Sandstones are fine grained; cross-sets are small scale and low angle.	FA1 associated with Sm facies			
Parallel laminated sandstone (Facies Sl)	Fine grained, pink colored, thick-bedded.	FA1 interbedded with St facies			
Red shale (Fm)	Red in color, faintly laminated	FA1 interbedded with Sl & Sm facies			
Herring-bone cross-bedded sandstone (Facies S-hb)	Medium grained, hard and compact sandstones, thick-and-thin bedded.	FA1, associated with Sp facies			
Interbedded shale and sandstone (Facies Fm-S)	Sandstones is medium to fine grained, thinly bedded	FA1 ,associated with Sp			
Tabular cross-bedded sandstone (Facies Sp)	Medium grained, hard and compact, large scale cross-beds.	FA2 associated with Sch & Sm facies	(215°)	1 (Baretha). 2 (Gchadi-Bajana). 4 (Holipura). 5 (Tantpur). 6 (Mewali). 7 (Bansi Paharpur). 8 (Jagnair). 9 (Rupbas). 10 (Gatouli). 11 (Bakoli). 12 (Tehra).	Tide and ebb channel
Parallel laminated sandstone (Facies Sl)	Medium grained, hard & compact, thick-bedded.	FA2 associated with Sp facies			
Massive sandstone (Facies Sm)	Medium grained, hard &compact.	FA2 associated with Sp facies			
Channel sandstone (Facies Sch)	Medium grained sandstones, fine laminations	FA2 associated with Sp facies			
Trough cross-bedded sandstone (Facies St)	Medium grained, pink, laminated, large scale cross-beds.	FA2 associated with Sp & Sl facies			
Tabular cross-bedded sandstone (Facies Sp)	Medium grained, pink sandstone large scale cross-sets	FA3 associated with Sl facies	(155°)	1 (Baretha). 3 (Rudawal). 11 (Bakoli). 12 (Tehra). 13 (Rasulpur).	Foreshore-offshore (Spit Platform)
Ripple-bedded sandstone (Facies Sr)	Medium grained, pink to white sandstone abundant asymmetrical ripple marks	FA3 associated with Sp facies			
Parallel-laminated sandstone (Facies Sl)	Medium grained, pink sandstone	FA3 associated with Sp facies			

The next 15m thick unit is thinly bedded tan colored shale with intercalated layers of siltstone and sandstone. This unit comprises parallel laminations (1mm to 4mm), thinly bedded fine grained sandstone facies association. The cross sets are small and dips at low angle. The symmetrical and asymmetrical ripple marks and bidirectional ripple cross laminations indicate both tidal traction currents and wave processes. The interlaminated siltstone and sandstone are the result of seasonally controlled fluctuations of sediment supply in tide dominated environment. Color banding in shale-siltstone may also indicate seasonal changes in chemistry at the sediment /water interface. Beds internally show thick-and-thin nature which implies influence of ebb and flood tidal currents. Presence of herring-bone cross-bed reflects the bed load deposition by reversing tidal currents of equal bed shear intensity and bottom current velocities. The dominant bimodal pattern represents a tidal current transport path and there is noticeable dominance of flood tide bedforms. These characteristics are indicative of deposition from suspension in shallow, quiet water juxtaposed by periodic input of tidal currents and waves, similar to the facies assemblage of the back barrier tidal flat environments (e.g., Phleger,1969; Reineck and Singh,1980 ; Hobday and Horne,1977 ; Fleming, 1977 ; Elliot,1978 ; Casshyap et al. , 2001; Allen and Leather, 2006).

The upper 5m thick unit of the Upper Bhander Sandstone comprises of facies characterised by well sorted sandstone, having symmetrical and asymmetrical ripples with crests oriented parallel to the current direction. This facies assemblage is characteristic of shallow water regime of backshore-shoreface environment. Planar bedded quartzarenite showing wave ripples, primarily low swash lamination dipping seaward cap the tidal flat sequence, reflecting a foreshore deposits.

The Upper Bhander Sandstone represents barrier island tidal inlet (channel fill) deposits comparable to other basin reported by Terwindt, 1971; Van Beek and Koster, 1972; Kumar and Sanders, 1974, 1975; Oomkens, 1974, Casshyap et al., 2001. The proposed depositional model for the Upper Bhander Sandstone represents a tidal inlet-barrier system with channel lag, ebb generated lenticular cross-bedsets with flood generated reactivation foresets and spits (beach foreshore) sub-environments (Figure 20) e.g., (Van Beek and Koster, 1972; Hayes, 1980; Terwindt, 1971; Van Beck and Koster, 1972; Kumar and Sanders, 1974, 1975; Oomkens, 1974, Casshyap et al., 2001).

The barrier inlet deposits, including the overlying foreshore facies, grow laterally by inlet migration along shore to produce coalescing, lenticular, elongate sand bodies and upward fining sequence, resembling modern analogues migrating tidal channels of barrier bars (e.g., Hoyt and Henry,1967; Kumar and Sanders,1974).

The mixed sandy and shaly tidal flats and washover fan deposits extended the back barrier portion landwards (westwards) (Figure 21A,B). Barrier inlet (tidal inlet) channel deposits, overlain by this veneer of spit/ beach or foreshore deposits, constitute the bulk of the preserved beach barrier complex. Truncated

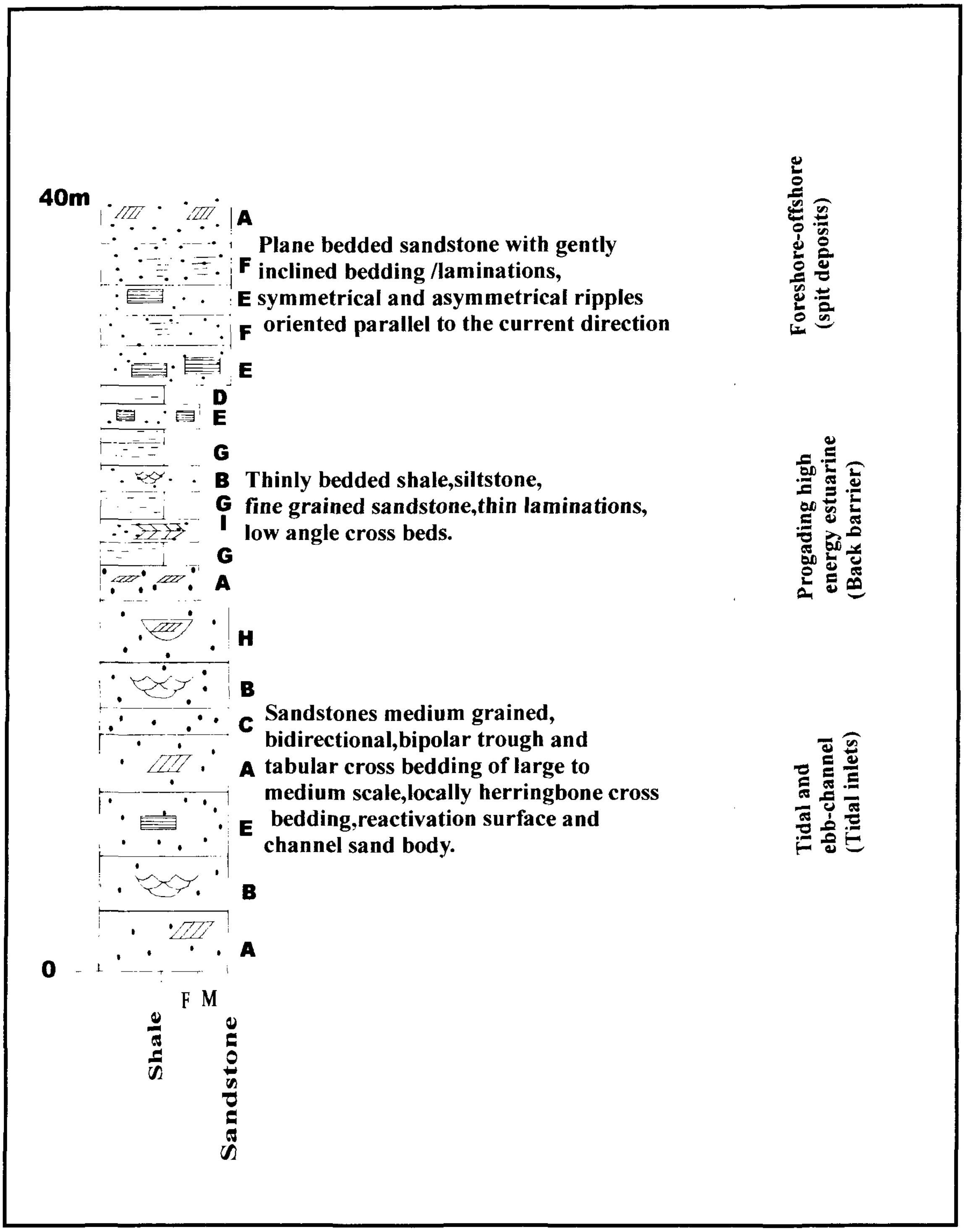


Figure 20 . A generalised sequence of the Upper Bhander Sandstone showing sedimentary facies, their characteristics and interpretation.

bedforms, thick and thin lenticular bodies of sandstone reflect waning flow in the shallowing tidal channel. Deposition by eastward directed ebb tidal current was more wide- spread than flood tidal and north-south oriented longshore littoral currents. Littoral drift has caused the updrift margin of the barrier inlet to migrate laterally parallel to shoreline by spit extension concomitantly with the erosion of downdrift inlet margin (Figure 21C). A combination of longshore migration of inlets and barrier transgression obliterates much of the typical sequence of barrier beach and shoreface sediments (Galloway and Hobday, 1983; Fitzgerald et al., 2004; Miner et al., 2005). As the surf zone moves landward across a shore zone that includes inlet fill as one of its thickest component, the subaerial to shallow subtidal portions are generally eroded. The process has left the beach complex sediments dominated by inlet fill deposits in the western and eastern parts (e.g., Kumar and Sanders, 1970; Galloway and Hobday, 1983; Kulp et al., 2007).

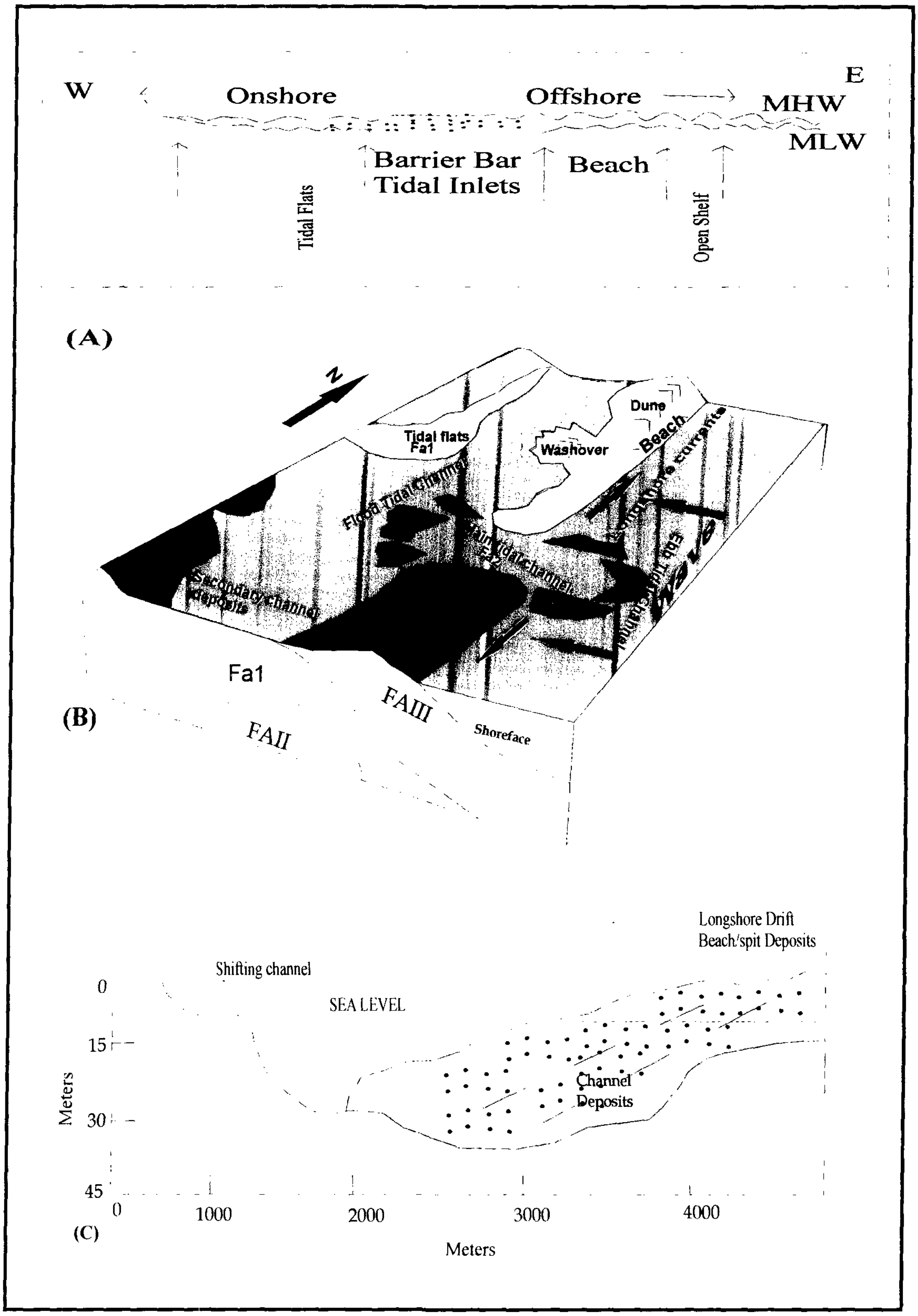


Figure 21 .(A) Schematic profile diagram of barrier island complex, showing the proposed major environmental setting of the Upper Bhander Sandstone from west to east;(B) Depositional Model; (C) schematic section of barrier inlet migration and lateral growth of inlet facies capped by thin foreshore/ spit deposit (modified from Henry and Hoyt,1967).

CHAPTER V

DETRITAL MINERALOGY

Sandstones are mixtures of mineral grains and rock fragments coming from naturally disintegrated products of erosion of rocks of all kinds. The detrital composition of sandstone is controlled by several factors such as tectonic settings (Dickinson and Suczek,1979; Ingersoll and Suczek, 1979; Valloni and Mazzardi,1984; Dickinson, 1985; Valloni,1985), transport mechanism (Lucchi, 1985; Velbel,1985), effect of climate (Suttner, 1974; Mack,1984; Basu, 1985; Suttner and Dutta,1986; Grantham and Velbel, 1988; Girty,1991; Akhtar and Ahmad,1991 and Khan,1995) and diagenetic modification (McBride,1985; Akhtar et al., 1992; Alam et al., 2000 ; Ahmad et al., 2004; Ahmad and Bhatt,2006; Ahmad et al.,2007,2008).

There are very few papers available in literature about the Upper Bhander Sandstone of Vindhyan Basin in southwestern parts of Uttar Pradesh and Rajasthan (Nazish, 1972; Mathur, 1985) that too on selective aspects. The present study of the Upper Bhander Sandstone deals with the identification of detrital mineral composition followed by classification.

Many workers have made attempts to categorize detrital quartz genetically because it is the chief and dominant constituent of sandstones and indicative of provenance. Sorby (1908) and Mackie (1896) were the first to study the detrital quartz grains. Mackie (1896) classified detrital quartz into four groups on the basis of their inclusions. Later, Krynine (1940, 1946) proposed genetic classification of detrital quartz into three types viz, igneous (plutonic, volcanic and hydrothermal vein quartz), metamorphic (recrystallised, schistose and stretched quartz) and reworked sedimentary quartz, on the basis of extinction, inclusion and grain shape. Krynine's plutonic quartz was modified to common quartz by Folk (1980) because most of the quartz from other sources (metamorphic, vein, etc.) has the same characteristics. Folk (1980) also classified detrital quartz empirically on the basis of extinction and inclusions.Blatt and Christie (1963) concluded that undulatory extinction is not a reliable guide to the provenance of quartz. Fuji (1958) recognized four varieties of quartz including cryptocrystalline quartz (chert).

Several workers (Folk and Weaver, 1952; Fuji, 1958; Folk, 1980) described chert as microcrystalline quartz, cryptocrystalline quartz and chalcedonic quartz. Chert was grouped into four varieties as fine grained, coarse grained, specular and silty (Pettijohn et al., 1987). Several workers now consider chert as rock fragment.

The significance of feldspar has been discussed in relation to source, paleoclimate and tectonism (Martens, 1931; Russell, 1939; Krynine, 1948; Hayes, 1962; Pittman, 1963; Rim Saite, 1967; Folk, 1980; Field and Pilkey, 1969; Pettijohn et al., 1987; Dickinson, 1985). Authegenic feldspar is believed to be a criterion of recognising marine origin (Crowley, 1939). The importance of metamorphic, sedimentary and volcanic rock fragments were described by Folk (1980), Pettijohn et al., (1987) and Pettijohn (1975).

Although, heavy minerals occur as accessory constituents of normal sandstone, they are considered to be useful guide to the type of source rock. Keeping this view in mind some definite assemblages of heavy minerals were described and related to their probable source rock (Boswell, 1933; Krumbein and Pettijohn, 1938; Feo-Codecido,1956; Pettijohn,1975; Fuji,1958; Ijima,1959; Baker ,1962;Okada , 1967; Folk ,1980; Mclarley,1981).

METHODS OF STUDY

In the present study detrital mineral composition of sandstone is evaluated both quantitatively and qualitatively.105 thin sections of the study area (13 from Rasulpur, 12 from Tehra, 5 from Bakoli, 6 from Rupbas, 6 from Gatouli, 7 from Mewali, 6 from Jagnair, 3 from Holipura, 8 from Tantpur, 11 from Baretha , 5 from Gchadi bajana,13 from Bansi Paharpur and 10 from Rudawal respectively) were selected to determine the modal composition and other petrographic characters of the Upper Bhander Sandstone. These samples were selected in such a way so as to uniformly cover, the outcrops of 13 sections of the Upper Bhander Sandstone in their lateral and vertical disposition. Thin sections of sandstone were quantitatively analysed for their percentage composition, using a swift automatic point counter fitted to a petrographic microscope. About 200 -300 grains were counted per slide for a uniform coverage of thin sections. Terminology of Krynine (1940) and Folk (1980) is followed for describing varieties of quartz and other framework constituents. Heavy minerals were separated by employing Milner's (1962) method.

DETRITAL MINERAL COMPOSITION

The studied sandstone samples are mainly composed of several varieties of quartz followed by feldspar, rock fragments, micas and heavy minerals. The average composition of detrital mineral are: monocrystalline quartz (90.98 percent), polycrystalline recrystallised metamorphic quartz (1.82 percent), stretched metamorphic quartz (1.76 percent), feldspar (2.10 percent), rock fragment (2.42 percent), mica and heavy minerals (0.92 percent) (Table 8).

QUARTZ

Quartz is the most dominant constituent and its varieties have been recognized on the basis of Folk`s (1980) classification scheme. Most of the quartz grains are monocrystalline, along with some polycrystalline grains. The monocrystalline quartz generally shows undulatory extinction. Polycrystalline quartz grains possess both sharp and sutured intercrystalline boundaries. The observed varieties of quartz are: common quartz, recrystallised metamorphic quartz and stretched metamorphic quartz. The average percentage of different quartz types are: common quartz (90 percent), polycrystalline recrystallised metamorphic quartz (2 percent) and stretched metamorphic quartz (2 percent) (Table 8).

COMMON QUARTZ

The sandstone under study consists of dominantly common quartz. It constitutes 89% to 96% (average 92.79%) in Rasulpur section, 88% to 94% (average 90.58%) in Tehra section, 86% to 92% (average 88.40 %) in Bakoli section, 90% to 92% (average 91.19%) in Rupbas section, 89% to 92% (average 90.70%) in Gatouli section, 88% to 92% (average 90.19%) in Mewali section, 90% to 96% (average 93.80%) in Jagnair section, 90% to 96% (average 92.20%) in Holipura section, 90% to 93% (average 90.89%) in Tantpur section, 91% to 95% (average 92.29%) in Baretha section, 88% to 91% (average 89.40%) in Gchadi bajana section, 86% to 92% (average 89.13%) in Bansi Paharpur section and 88% to 94% (average 90.20%) in Rudawal section (Table 8).

It occurs as irregular subequant and mostly subrounded to sub angular grains. But angular and rounded grains are also common. The quartz shows straight to slightly undulose extinction. Mineral inclusions are commonly of micas, zircon, tourmaline and opaques. This type of quartz was termed as plutonic quartz by Krynine (1940) and common quartz by Folk (1980).

RECRYSTALLISED METAMORPHIC QUARTZ

Recrystallised metamorphic quartz comprises 1% to 3% (average 1.77%) in Rasulpur section, 0 to 4% (average 2.79%) in Tehra section, 2% to 5% (average 3.40%) in Bakoli section, 0 to 3% (average 1.33%) in Rupbas section, 0 to 5% (average 1.83%) in Ghatouli section, 1% to 4% (average 2.75%) in Mewali section, 0 to 2% (average 0.66%) in Jagnair section,2% to 3% (average 2.66%) in Holipura section, 0 to 3% (average 1.25%) in Tantpur section, 1% to 4% (averages 1.00%) in Baretha section, 0 to 4% (average 2.20%) in Gchadi bajana section,0 to 3% (average 1.53%) in Bansi Paharpur section, 1% to 4% (average 2.30%) in Rudawal section (Table 8).

Table 8 -Percentage of detrital mineral of the Upper Bhander Sandstone in parts of Uttar Pradesh -Rajasthan States.

Sample No.	Monocrystalline Quartz	Polycrystalline Quartz		Mica	Chert	Feldspar		Rock Fragment	
	Common	Recrystallised Metamorphic	Stretched Metamorphic			Microcline	Plagioclase	Sedimentary	Metamorphic
Rasulpur Section									
R1	92	1	-	-	-	3	2	1	1
R2	91	1	1	2	1	1	1	1	1
R3	90	3	2	2		1	1	1	1
R4	95	1	1	-	-	1	1	1	-
R5	96	2	-	-	1	-	-	-	1
R6	92	2	2	2		-	-	1	-
R7	89	2	4	-	1	1	2	2	-
R8	95	2	-	1		-	-	1	-
R9	90	3	3	-	1	-	1	1	1
R10	92	2	1	1	1	1	1	-	2
R11	96	1	-	-	1	-	-	1	-
R12	93	1	2	-	2	-	-	1	1
R13	95	2	-	1	-	-	-	2	-
Average	92.79	1.77	1.23	0.69	0.61	0.61	0.69	1	0.61
Tehra Section									
T1	91	4	-	1	-	-	1	1	2
T3	91	2	2	1	1	2	-	-	1
T4	90	4	2	2	-	-	-	-	2
T5	89	3	2	1	1	1	1	1	1
T6	94	3	-	1	-	-	1	1	-
T7	90	4	4	1	-	-	-	-	1
T8	91	-	2	2	1	1	1	1	1
T9	90	4	-	1	1	1	1	1	1
T10	90	2	5	1	-	-	1	1	-
T11	91	1	2	1	1	1	1	1	1
T12	92	4	1	2	-	-	-	-	1
T13	88	2	3	2	1	1	1	1	1

Average	90.58	2.79	1.95	1.08	0.50	0.58	0.66	0.66	1
Bakoli Section									
B1	87	3	2	1	2	1	2	1	1
B2	90	4	-	1	1	-	1	2	1
B3	86	5	2	1	2	1	1	1	1
B4	92	2	2	1	-	-	1	1	1
B5	87	3	2	1	2	1	2	1	1
Average	88.40	3.40	1.60	1	1.4	0.6	1.40	1.20	1
Rupbas Section									
RP1	91	2	2	1	-	1	1	1	1
RP2	92	-	3	1	1	1	2	-	-
RP3	91	1	3	1	-	-	3	-	1
RP4	90	3	2	1	-	-	2	1	1
RP5	91	2	2	1	-	1	1	1	1
RP6	92	-	3	1	1	1	2	-	-
Average	91.19	1.33	2.50	1	0.33	0.66	1.83	0.50	0.66
Gatouli Section									
GH1	90	-	3	1	1	1	2	1	1
GH2	89	2	2	1	-	3	1	1	1
GH3	92	-	-	1	-	2	4	1	-
GH4	90	5	-	1	-	2	1	1	-
GH5	92	3	-	-	-	2	2	-	1
GH6	90	1	-	1	2	2	1	2	1
Average	90.70	1.83	0.83	0.83	0.50	2	1.83	1	0.66
Mewali Section									
M1	90	4	3	1	2	-	-	-	-
M2	88	3	4	1	-	1	1	1	1
M3	90	2	3	1	-	1	2	1	-
M4	90	3	5	1	-	-	-	1	-
M5	91	3	3		-	1	-	1	1
M6	90	1	4	1	-	2	1	1	-
M7	92	2	1	1	1	-	1	1	1
Average	90.19	2.57	3.28	0.85	0.42	0.71	0.71	0.85	0.42
Jagnair Section									
J1	93	2	2	1	1	-	1	-	-

J2	95	1	2	1	-	-	-	-	1
J3	96	-	3	1	-	-	-	-	-
J4	92	-	4	1	-	-	1	1	1
J5	95	-	1	1	1	-	1	-	1
J7	90	1	1	1	1	2	1	2	1
Average	93.80	0.66	2.16	1	0.50	0.33	0.66	0.50	0.66
Holipura Section									
HP1	90	3	-	1	1	-	4	-	1
HP2	90	3	-	1	1	-	2	2	1
HP3	96	2	-	1	-	-	-	1	-
Average	92.20	2.66	0	1	0.66	0	2	1	0.66
Tantpur Section									
TT1	90	1	3	1	1	-	2	1	1
TT2	93	1	1	1	-	-	3	1	-
TT3	91	-	2	1	-	2	2	1	1
TT4	90	3	1	1	1	1	2	-	1
TT5	90	2	1	1	-	2	3	-	1
TT6	91	1	1	1	2	-	2	1	1
TT7	92	1	1	1	-	-	3	1	1
TT8	90	1	2	1	1	1	3	-	1
Average	90.89	1.25	1.50	1	0.62	0.75	2.50	0.62	0.87
Baretha Section									
BD1	91	1	-	1	1	1	2	2	1
BD2	93	-	2	1	1	-	1	1	1
BD3	91	1	1	1	1	1	1	2	1
BD4	95	-	-	1	1	-	1	1	1
BD5	93	-	1	1	1	1	1	1	1
BD6	95	-	-	-	1	1	1	1	1
BD7	91	2	1	-	2	2	-	1	1
BD8	93	1	1	-	1	1	2	-	1
BD9	91	1	1	1	2	1	2	-	1
BD10	91	4	1	-	2	-	-	-	2
BD11	91	1	2	1	1	1	2	-	1
Average	92.29	1	0.29	0.63	1.27	0.81	1.18	0.81	1.09
Gchadi Bajana Section									
G1	91	3	2	1	-	-	2	1	-

G2	90	3	2	1	-	-	2	1	1
G3	89	1	4		1	-	2	2	1
G4	89	4	2	1	-	-	2	1	1
G5	88	-	4	-	2	2	-	3	1
Average	89.40	2.20	2.80	.0.60	0.60	0.40	1.60	1.60	0.80
Bansi Paharpur Section									
BP1	90	1	2	1	-	1	2	2	1
BP2	92	-	2	1	-	1	1	1	2
BP3	92	1	1	1	-	2	2	1	-
BP4	89	1	3	1	1	1	2	1	1
BP5	87	2	2	2	1	2	2	1	1
BP6	86	3	3	1	1	-	3	2	1
BP7	90	1	2	1	1	2	1	1	1
BP8	89	1	4	1	1	-	2	2	1
BP9	88	2	3	1	-	2	1	2	1
BP10	90	3	4	-	-	1	-	1	1
BP11	88	2	3	3	-	1	1	1	1
BP12	89	1	2	3	-	1	2	1	1
BP13	89	2	2	1	-	1	2	2	1
Average	89.13	1.53	2.53	1.30	0.38	1.15	1.61	1.38	0.99
Rudawal Section									
RD1	90	2	3	-	1	-	2	1	1
RD2	89	3	3	-	-	1	2	1	1
RD3	88	4	2	1	1	1	1	1	1
RD4	88	4	2	1	-	-	2	2	1
RD5	89	2	4	-	1	1	1	1	1
RD6	89	2	2	1	-	2	2	1	1
RD7	94	1	3	1	-	-	-	-	1
RD8	93	1	2	1	-	1	1	-	1
RD9	91	3	3	1	-	-	-	1	1
RD10	91	1	-	-	2	2	2	1	1
Average	90.20	2.30	2.40	0.60	0.50	0.80	1.30	0.90	1
Average Area Level	90.98	1.82	1.76	0.92	0.64	0.77	1.33	0.92	0.86

It occurs as composite grains of fine to medium size and equant to subequant shape (Plate-VA). The quartz grains make up a mosaic of microcrystalline and fine grained varieties. The grains are equidimenssional with straight boundaries, show different optic orientation and straight extinction. The grains are mostly subrounded to rounded but subangular grains are also common. The size and roundness of recrystallised metamorphic quartz grains are comparable to that of the chert grains. Presence of minute mica flakes and clay impurities are common.

STRETCHED METAMORPHIC QUARTZ

This type of quartz is dominant in Rasulpur section 0 to 4% (average 1.23%), in Tehra section 0 to 5% (average 1.95%), in Bakoli section 0 to 2% (average 1.60%), in Rupbas section 2% to 3% (average 2.50%),in Gatouli section 0 to 3% (average 0.83%), in Mewali section 1% to 5% (average 3.28%),in Jagnair section 1% to 4% (average 2.16%), in Tantpur section 1% to 3% (average 1.50%), in Baretha section 0 to 2% (average 0.29%), in Gchadi bajana section 2% to 4% (average 2.80%),in Bansi Paharpur section 1% to 4% (average 2.53%) and in Rudawal section 0 to 4% (average 2.40%) (Table 8).

It occurs in the form of subrounded to well rounded polycrystalline grains which are mostly made up of elongated and lensoid sub-individuals of quartz. The sub-individuals are in sub-parallel to almost parallel orientation with smooth and sutured boundaries (Plate-VA). The sub-individuals show highly undulose extinction. Sometimes the sub individuals occur independently as monocrystalline grains which are easily recognized and distinguished from monocrystalline common quartz by characteristic features such as elongated and lensoid shape, abundant healed fractures and highly undulose extinction.

FELDSPAR

The detrital feldspar includes both fresh and altered feldspar. Feldspar is present in small amount, in Rasulpur section 0 to 3% (average 0.65%), in Tehra section 0 to 2% (average 1.00%), in Bakoli section 0 to 2% (average 1.00%), in Rupbas section 0 to 3% (average 1.16%), in Gatouli section 1% to 4% (average 1.90%), in Mewali section 0 to 2% (average 0.71%), in Jagnair section 0 to 2% (average 0.50%), in Holipura section 0 to 4% (average 1.00%), in Tantpur section 0 to 3% (average 1.62%), in Baretha section 0 to 2% (average 1.00%), in Gchadi bajana section 0 to 2% (average 1.00%) ,in Bansi Paharpur section 0 to 3% (average1.38%) and in Rudawal section 0 to 2% (average 1.05%) (Table 8) .

Two varieties of feldspar have been recognized which include microcline and plagioclase (Plate-VB). Altered feldspars (plagioclase and microcline) have a dusty appearance under plane polarized light. Their interference colors possess shades of grey and brown.

CHERT

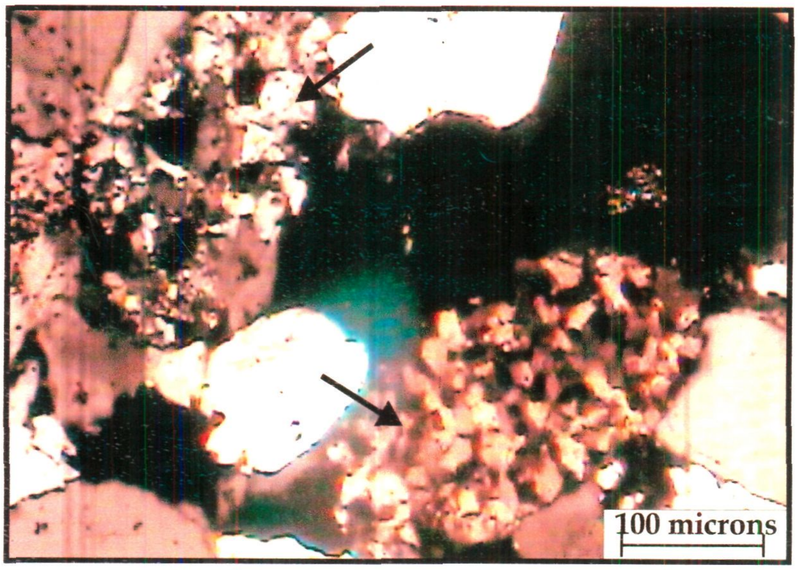
Chert is present in variable amount in the different sections, in Rasulpur section 0 to 2% (average 0.61%), in Tehra section 0 to 1% (average 0.50%), in Bakoli section 0 to 2% (average 1.40%), in Rupbas section 0 to 1% (average 0.33%), in Gatouli section 0 to 2% (average 0.50%), in Mewali section 0 to 2% (average 0.42%),in Jagnair section 0 to 1% (average 0.50%), in Holipura section 0 to 1% (averages 0.66%), in Tantpur section 0 to 2% (average 0.62%), in Baretha section 1% to 2% (average 1.27%), in Gchadi bajana section 0 to 2% (average 0.60%),in Bansi Paharpur section 0 to 1% (average 0.38%) and in Rudawal section 0 to 2% (average 0.50%) (Table 8).

The chert grains occur as subrounded to well rounded grains which are approximately smaller than the accompanying quartz grains (Plate-VC). But in some cases these are larger or equal to quartz grains in size. It also occurs as cementing material between the quartz grains .Chalcedony grains show radiating extremely thin fibers under crossed nicols .Chert grains contain common impurities of clay ,silt and iron oxide. The presence of chert like that of multicyclic quartz indicates the presence of sedimentary / or metasedimentary rocks in the provenance.

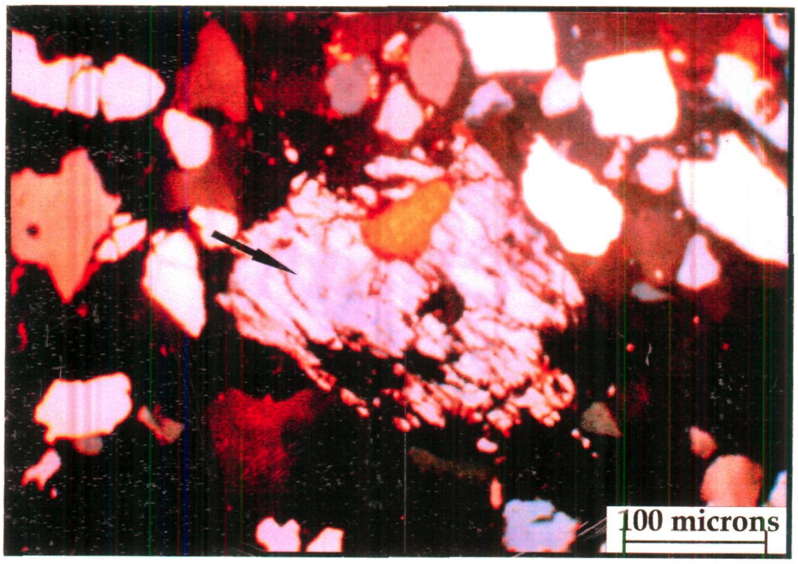
ROCK FRAGMENTS

Besides fragments of chert described earlier, sedimentary and metamorphic rock fragments are sparsely distributed. Quartzite and schist by and large are the most common varieties of rock fragments present in the sandstones. Rock fragments constitute very small component of each section for example, in Rasulpur section 0 to 2% (average 0.72), in Tehra section 0 to 2% (average 0.74%), in Bakoli section 0 to 2% (average 1.13%), in Rupbas section 0 to 1% (average 0.50%),in Gatouli section 0 to 2% (average 0.72%), in Mewali section 0 to 1% (average 0.64%), in Jagnair section 0 to 2% (average 0.50%), in Holipura section 0 to 2%

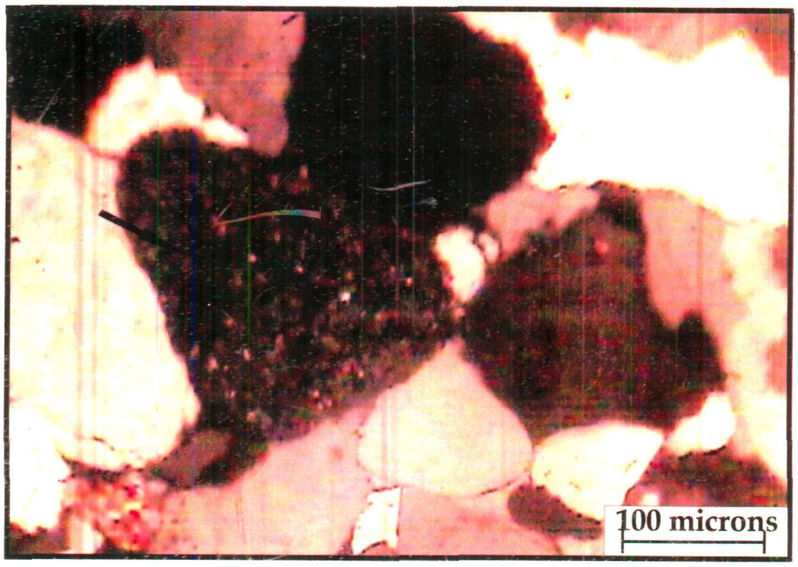
PLATE V



A



B



C

PLATE V

A. Photograph showing polycrystalline recrystallised metamorphic quartz and stretched metamorphic quartz.

B. Photomicrograph showing plagioclase feldspar grain.

C. Photomicrograph showing chert grain

(average 0.83%),in Tantpur section 0 to 1% (average 0.75%), in Baretha section 0 to 2% (average 0.95%), in Gchadi bajana section 0 to 3% (average 1.20%),in Bansi Paharpur section 0 to 2% (average 1.19%) and in Rudawal section 0 to 2% (average 0.95%) (Table 8).

The sedimentary rock fragments include chert, shale and siltstone. They are subrounded to well rounded and their size is similar to that of surrounding quartz grains. Due to their incompetent nature, the shale fragments have been squeezed occasionally in between the surrounding quartz grains giving rise to pseudo matrix.

Metamorphic rock fragments include phyllite, schist (Plate-VIA) and quartzite. Grains of quartzite and schist are uniformly, though sparsely distributed in all the sandstone samples. They are of the same order of size as the detrital quartz grains, but are relatively rounded to sub rounded than the latter.

MICA

Mica grains occur as traces in all the 13 sections of the Bhander Sandstone. They include muscovite and biotite. Their percentage ranges from 0 to 2% in Rasulpur section (average 0.69%), in Tehra section 1% to 2% (average 1.08%), in Bakoli section upto 1% (average 1.00%), in Rupbas section upto 1% (average 1.00%), in Gatouli section 0 to 1% (average 0.83%), in Mewali section 0 to 1% (average 0.85%), in Jagnair section upto 1% (average 1.00%), in Holipura section upto 1% (average 1.00%), in Tantpur section upto 1% (average 1.00%), in Baretha section 0 to 1% (average 0.63%), in Gchadi bajana section 0 to 1% (average 0.60%), in Bansi Paharpur section 0 to 3% (average 1.30%) and in Rudawal section 0 to 1% (average 0.60%) (Table 8) . They are randomly distributed as grains. Muscovite commonly occurs as altered form originated from orthoclase. Both muscovite and biotite occur as tiny large elongate flakes with frayed ends. The flakes occasionally show mechanical deformation as the result of pressure by the accompanying quartz grains (Plate-VIB). Biotite grains are generally brown in color.

HEAVY MINERALS

In addition to the above described framework constituent of the Upper Bhander Sandstone, a suite of the following heavy minerals is also observed.

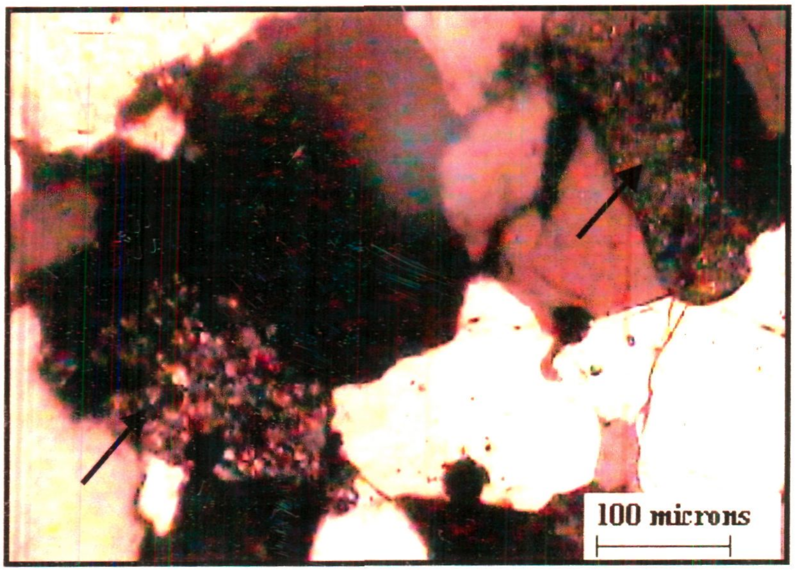
Opaques: Opaques forms the major part of the heavy mineral crop in this study. Three varieties of opaques (in reflected light) viz., limonite, goethite and magnetite are identified. These opaque grains are subangular to sub rounded.

Tourmaline: Brown, pink and blue varieties of tourmaline are seen. Some grains are nearly perfectly rounded while other show remnants of original crystal outline. They are full of inclusions.

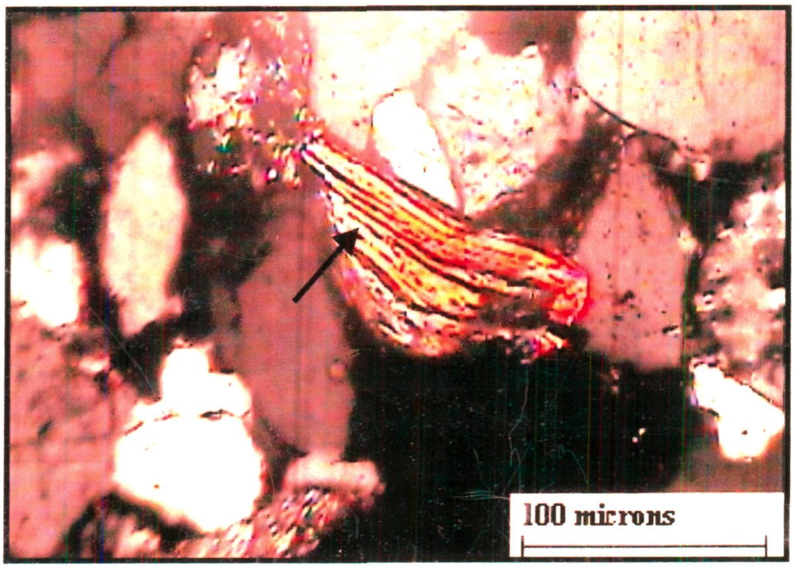
Zircon: Zircon grains are pyramidal in shape with angular to subrounded boundaries. The most common variety is colorless. They contain some inclusions of opaque and other minerals.

Biotite: Biotite grains are prismatic or subrounded with irregular outlines. Pale brown variety of biotite is common.

PLATE VI



A



B

PLATE VI

A. Photomicrograph showing phyllite and schist fragments.

B. Photomicrograph showing muscovite flakes affected by mechanical compaction.

Epidote: Pale greenish variety of epidote has been identified in these sandstones. The grains are subangular to sub rounded.

Garnet: The colorless variety is most abundant. Most grains show abraded margins and are angular to subrounded in shape.

Rutile: Brownish red to yellow varieties of rutile are present. The grains are angular to rounded.

Staurolite: Brownish yellow variety of staurolite has been identified in these sandstones. These grains are irregular, subangular to subrounded with subconchoidal fractures.

Hornblende: Hornblende shows a characteristic green color. Usually the grains are elongate and irregularly terminated.

CLASSIFICATION OF SANDSTONE BASED ON FOLKS SCHEME

Folk (1980) used a triangular diagram allotting all types of quartz including metaquartzite (but not chert) to quartz pole (Q), all single feldspar including granite and gneiss fragments to feldspar pole (F) and all other rock fragments (chert, slate, phyllite, schist, volcanics, limestone, sandstone, shale) to rock fragment pole (R), ignoring the percentage to clay matrix, chemically precipitated cements, glauconite, phosphate, fossils, heavy minerals, mica, etc. According to Folk's classification scheme, sandstone was grouped into seven classes viz., quartzarenite, subarkose, arkose, lithicarenite, sublitharenite, feldspathic litharenite and litharenite. For classifying the studied Sandstone, all essential constituents were recalculated to 100 % and allotted to one of the three following poles:

Q- All types of quartz; common quartz, recrystallised metamorphic quartz and stretched metamorphic quartz.

F- All single feldspar grains plus granite and gneiss fragments.

R- All types of rock fragments; chert, shale, phyllite, schist, siltstone, limestone etc.

The average composition of framework grains of the Upper Bhander Sandstone is as follows: Quartz- 96%, Feldspar – 2% and Rock fragments – 2% (Table 9). All the samples of the studied sandstone plotted near the Q pole, in the quartzarenite field (Figure 22).

FACTORS CONTROLLING DETRITAL MINERALOGY

DISTANCE OF TRANSPORT

Distance of transport is one of the factors which control the composition at the time of deposition. The processes of mechanical breakdown, abrasion, hydrodynamic sorting during transportation, and result in compositional maturation of detritus into more quartzose detrital mode. The percentage of rock fragments, feldspar and polycrystalline quartz decreases with increase in transport distance and /or reworking (Blatt, 1967; Franzinelli and Potter, 1983; Lucchi, 1985). Large stream flow shows few or no change in mineral composition even during prolonged transport and whatever feeble changes that occur are not the result of differential abrasion (Russell, 1939).

Table 9. Percentage of framework modes of the Upper Bhander Sandstone in parts of Uttar Pradesh - Rajasthan States.

Sample No.	Qt	F	L
Rasulpur Section			
R1	93	5	2
R2	96	2	2
R3	97	2	1
R4	97	2	1
R5	99	0	1
R6	98	0	2
R7	96	3	1
R8	98	0	2
R9	97	1	2
R10	97	2	1
R11	98	0	2
R12	98	0	2
R13	98	0	2
Tehra Section			
T1	96	1	3
T3	97	2	1
T4	98	0	2
T5	96	2	2
T6	98	1	1
T7	99	0	1
T8	96	2	2
T9	96	2	2
T10	98	1	1
T11	96	2	2
T12	99	0	1
T13	96	2	2
Bakoli Section			
B1	95	3	2
B2	96	1	3
B3	96	2	2
B4	97	1	2
B5	95	3	2
Rupbas Section			
RP1	96	2	2
RP2	97	3	0
RP3	96	3	1
RP4	96	2	2
RP5	96	2	2
RP6	97	3	0
Gatouli Section			
GH1	95	3	2
GH2	94	4	2

GH3	93	6	1
GH4	96	3	1
GH5	95	4	1
GH6	94	3	3
Mewali Section			
M1	100	0	0
M2	96	2	2
M3	96	3	1
M4	99	0	1
M5	97	1	2
M6	96	3	1
M7	97	1	2
Jagnair Section			
J1	99	1	0
J2	99	0	1
J3	100	0	0
J4	97	1	2
J5	98	1	1
J7	94	3	3
Holipura Section			
HP1	95	4	1
HP2	95	2	3
HP3	99	0	1
Tantpur Section			
TT1	96	2	2
TT2	96	3	1
TT3	94	4	2
TT4	96	3	1
TT5	94	5	1
TT6	96	2	2
TT7	95	3	2
TT8	95	4	1
Baretha Section			
BD1	94	3	3
BD2	97	1	2
BD3	95	2	3
BD4	97	1	2
BD5	96	2	2
BD6	96	2	2
BD7	96	2	2
BD8	96	3	1
BD9	98	0	2
BD10	96	3	1
BD11	98	0	2
Gchadi Bajana Section			
G1	97	2	1
G2	96	2	2

G3	95	2	3
G4	96	2	2
G5	94	2	4
Bansi Paharpur Section			
BP1	94	3	3
BP2	95	2	3
BP3	95	4	1
BP4	95	3	2
BP5	94	4	2
BP6	94	3	3
BP7	95	3	2
BP8	95	2	3
BP9	94	3	3
BP10	97	1	2
BP11	96	2	2
BP12	95	3	2
BP13	94	3	3
Rudawal Section			
RD1	96	2	2
RD2	95	3	2
RD3	96	2	2
RD4	95	2	3
RD5	96	2	2
RD6	94	4	2
RD7	99	0	1
RD8	97	2	1
RD9	98	0	2
RD10	94	4	2
Area Level Average	96	2	2

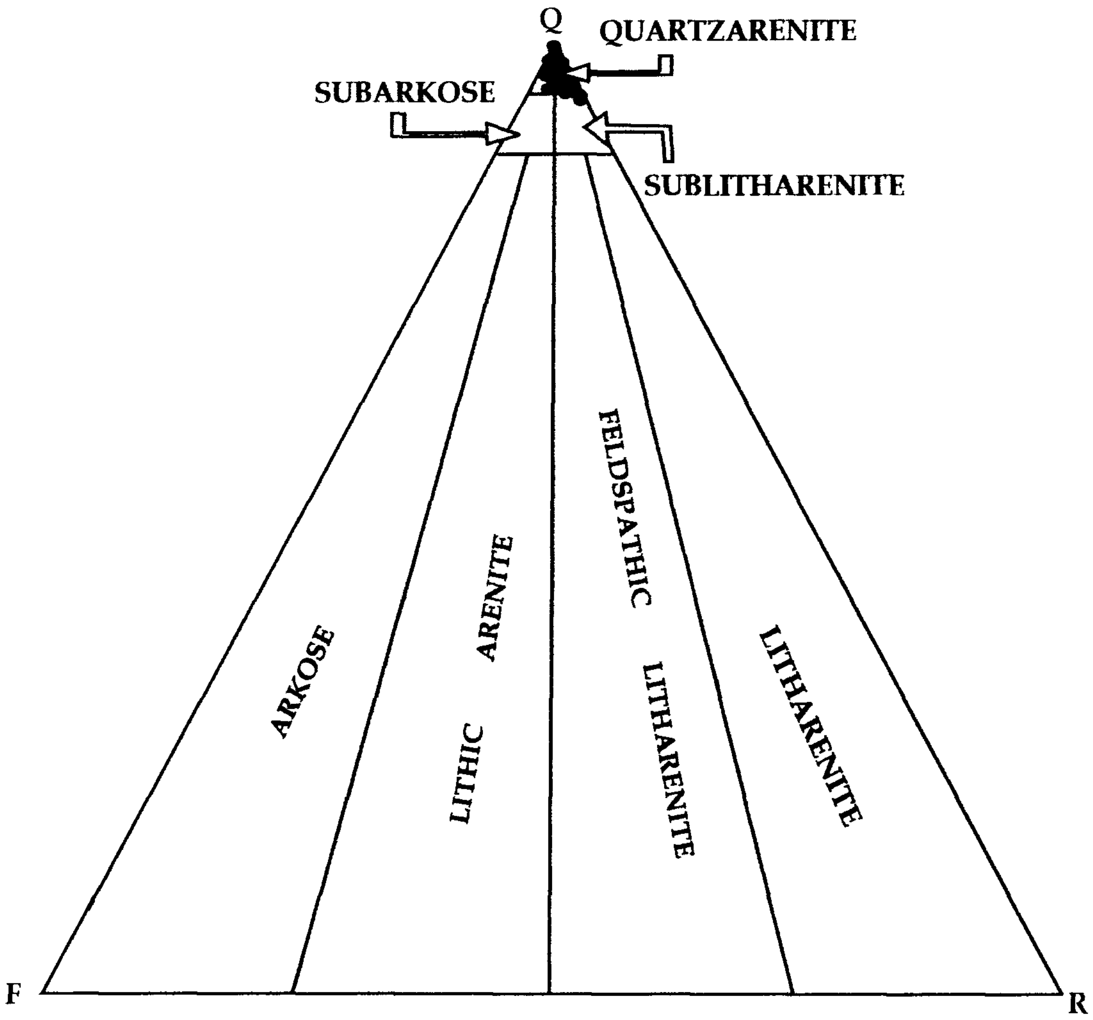


Figure 22. Classification of the Upper Bhander Sandstone according to Folk (1980)

The detrital grains of the Upper Bhander Sandstone of the Vindhyan Basin are in the sand size range and probably they have undergone transportation for a distance of a few hundred kilometers. The presence of small amount of feldspar and rock fragments in the studied sandstones may be due to the transportation of sediments by high gradient streams and rapid destruction of feldspar by abrasion. Since the deposition of the Upper Bhander Sandstone took place in a tectonically rifted basin, presence of high gradient stream is quite likely within the basin.

DIAGENETIC MODIFICATION

The detrital composition of sands may be altered by diagenetic processes, which must be taken into considerations, while making provenance interpretation (McBride, 1985). The diagenetic modification include loss of detrital framework grains by dissolution, alteration of grains by replacement or recrystallisation and the loss of identity of certain ductile grains during compaction, which give rise to pseudomatrix.

The presence of weathered feldspar grains as well as oversize pores indicates dissolution of detrital grains in the studied sandstone. The replacement of quartz grains by iron in some thin sections suggests slight modification of the composition of the sandstone. The study of grain contacts of the Upper Bhander Sandstone indicates that the sandstones are subjected to compaction during burial and their original texture and fabric slightly modified by the process of compaction.

SOURCE ROCK COMPOSITION

Among the several factors influencing the detrital mineralogy of sandstones, the lithological composition of the rocks in the source area may be the most potent and dominating agent that affects the final sandstone composition (Krynine, 1948).

The various types of source rocks produce different suite of detrital minerals which reveal the character of that rock from which the suites have originated. A study of both the light and heavy minerals of the sandstone is important in interpreting the provenance character. Among the light minerals, quartz is the dominant constituent of the sandstone. Therefore, study of detrital quartz can provide an insight to the ultimate source of rocks.

Krynine (1946) used quartz as a guide to the provenance. His approach was based on grain shape, type of inclusion and extinctions (undulatory and non – undulatory). It was presumed that a discrimination between igneous (plutonic) and metamorphic origins of common monocrystalline quartz could be made on the above mentioned basis, but such criteria are usually difficult to apply (Bokmann, 1952). Quartz of the source rock shows that difference in inclusions and shape, etc., either does not exist or may show a wide range of variation.

Many workers have emphasized the usefulness of polycrystalline or composite quartz (Voll, 1960; Blatt and Christie, 1963; Conolly, 1965; Basu, 1985). The polycrystalline quartz showing two distinctly different sizes of crystals within a single grain is diagnostic of metamorphic quartz. A high ratio of polycrystalline quartz to total quartz also suggests a metamorphic source. Voll (1960) noted two types of polycrystalline quartz of metamorphic origin, (1) polycrystalline quartz in which component grains form polygonal units, with straight boundaries which tend to meet at 120 degree angles and (2) polycrystalline quartz which exhibit sutured boundaries.

Basu et al., (1975) used the criteria of undulosity and polycrystallinity in his studies and concluded that higher proportion of moderately to strongly undulose monocrystalline quartz grain (undulosity >5°) and higher proportion of polycrystalline quartz in medium sand size is characteristic of metamorphic source. Plutonic rocks tend to provide non- undulose or weakly undulose (undulosity <5°) monocrystalline quartz grains and polycrystalline quartz grains with only two or three sub grains. Folk (1980) has identified undulosity and polycrystallinity in detrital quartz grains from different source rocks. Young (1976) used the internal fabric of polycrystalline quartz for inferring the source rock.

Feldspar is the second most common mineral of sand and because of this ubiquity feldspars have long been used as provenance indicator for sandstones. Because of their unstable nature, feldspars may be selectively modified or removed from the detritus during weathering, transportation and diagenesis, resulting in decrease of their effectiveness as a provenance indicator.

The feldspar grains in sandstone may be derived from different source and show the variation in their chemical and physical properties which have genetic implication. The properties of feldspars used to decipher different provenance include their chemical compositions, zoning, twinning and structural state.

Zoning in feldspar is also very important because type of zoning /or lack of it may serve as a clue to the provenance of the feldspar (Pittman, 1963). The plagioclase in volcanic and hypabyssal rocks is characterised by oscillatory zoning where as this type of zoning is rare in plutonic igneous and metamorphic rocks. Trevena and Nash (1981) too obtained similar results. Correlation of twinning with host rock lithology has been attempted by many workers (Gorai, 1951; Turner, 1951; Tobi, 1962). The twinning of K- feldspar has been utilized in provenance studies to distinguish microcline bearing rocks from those rich in orthoclase or sanidine. Plymate and Suttner (1983) found that frequency of cross- hatched twinning is a quick method for correlating K-feldspar bearing sandstone with their source rock.

Feldspars are very sensitive to the weathering process which requires suitable climate as well as a proper length of time. The duration of time through which processes of decomposition act is determined by relief. The presence or absence of feldspar is the result of the balance between rate of erosion and decomposition. Therefore, detrital feldspar is an index of both climatic vigor and tectonism.

Both the varieties of mica, muscovite and biotite occur in sandstone. These are derived from metamorphic, plutonic and rarely from volcanic rocks. The muscovite is chemically more stable than biotite. In general, abundant micas are suggestive of metamorphic provenance.

Rock fragments are among the most informative of all the detrital components. Sandstone commonly contains rock particles of volcanic, sedimentary (mainly pelitic) and metamorphic origin (slate, phyllite, mica schist, etc.). They carry their own evidence of provenance (Bogg, 1968).

Heavy minerals provide exceptionally useful clue to the nature of source rocks. Like lighter fractions, they too are influenced by weathering, transportation and diagenesis. Important contribution in this field are those of Krynine (1964); Vintage (1957); McCarley (1981); Holland (1984); Zimmerle (1984); Morton (1985); Faupl and Wagreich (1992) and Faupl et al., (2002).

The Sandstones of the study area contain quartz of igneous (common quartz) and metamorphic (recrystallised metamorphic quartz, stretched metamorphic quartz) origin as well as micas, rock fragments, heavy mineral and feldspar. The most abundant quartz is common quartz. It is mainly derived from granitic batholiths or granite gneisses. The recrystallised quartz indicates an origin from metaquartzite, highly metamorphosed granite and gneissic rocks. The stretched quartz was, probably, derived from granites or schist.

Micas present in the studied sandstone samples are mainly muscovite and a few biotite grains derived, probably from granites, pegmatites or schist. The presence of abundant opaque grains in these sandstones reflects their derivation from metamorphic rocks. The suite of heavy minerals including biotite, tourmaline and zircon indicates igneous (plutonic) source for these sediments. On the other hand the suite of heavy minerals including garnet, staurolite and epidote reflect metamorphic source for these sediments (Morton, 1985; Wanas and Abdel-Maguid, 2006). The suite of heavy minerals including rounded grains of rutile, tourmaline and zircon is indicative of the reworked source for these sandstones. Presence of alkali feldspar indicates their source as both plutonic and metamorphic rocks but abundant microcline feldspar indicates granitic as well as pegmatitic source. From the above discussion, interpretation can be drawn that the sediments of the Upper Bhander Sandstone were derived from a variety of source rocks (mixed provenance).

The mineralogical maturity of heavy mineral assemblage of source rocks is defined by Zircon-Tourmaline-Rutile index (Z-T-R). It is the percentage of combined zircon, tourmaline and rutile grains among the transparent, non-micaceous detrital heavy minerals (Hubert, 1962). The Z-T-R index value calculated for the Upper Bhander Sandstone is 79.16. Thus the high Z-T-R value along with low percentage of rock fragments and feldspars in the studied sandstone indicates prolonged abrasion or high intensity of weathering in the source area.

CHAPTER VI

PETROFACIES AND TECTONO-PROVENANCE

INTRODUCTION

Petrofacies, as defined by Dickinson and Rich (1972), implies detrital composition of sandstone and its significance to regional tectonic framework and contemporary tectonic activity in the source and depositional areas. The sandstone petrofacies analysis have been effectively employed for deciphering provenance and its tectonic setup, source rock composition, role of climate and transport which are in turn applied to interpret correctly the tectono-sedimentary evolution of geoprovince and its sedimentary cover (Dickinson et al., 1983; Mack, 1984; Schwab, 1991; Graham et al., 1976; Cox and Lowe, 1995).The relationship between plate-tectonics and sandstone composition has been the subject of intensive research and discussion over the last three decades. Many studies have pointed to an intimate relationship between detrital sand composition and tectonic setting (Crook,1974; Ingersoll,1978; Potter,1978; Dickinson and Suczek,1979; Ingersoll and Suczek,1979; Dickinson and Valloni,1980; Schwab,1981; Valloni and Mezzardi,1984; Bhatia,1985; Dickinson,1985, Bhatia and Crook,1986; Schwab, 1986; Garzanti,1986; Stefani,1987;De Celles and Hertel,1989 ; Akhtar and Ahmad,1991; Akhtar et al.,1994; Cox and Lowe,1995; Critelli,1999;Arribas et al.,2003;Ahmad and Bhat,2006; Ahmad et al.,2007,2008).

The proportion of detrital framework grains plotted in triangular diagram provides effective discrimination of a variety of plate-tectonic settings and have been used as a powerful tool for determining the origin and tectonic reconstruction of terrigenous deposits (Graham et al., 1976; Dickinson, 1985). But, sometimes correlation between tectonic setting and sandstone petrofacies does not hold well due to other factors that influence the detrital mineralogy of sandstone. These must be taken into account at the time of interpretation of provenance and tectonic setting (Mack, 1984; Zuffa, 1985; Ingersoll, 1990). Johnson (1993) gave a detailed account of the various sedimentary processes that control evolution of detrital composition and their role in the modification of original composition of detritus. Climate and relief play most important role in this regard. During the process of pedogenesis they can obscure the composition of detritus to the extent of its total loss of tectonic inheritance. The tropical warm and humid climate aided by low relief that result in intense chemical weathering, is the most effective agent of modification of original detrital composition (Suttner et al.,1981; Basu,1985; Grantham and Velbel,1988; Girty,1991). Other modifying agents are sediment transport across tectonic boundaries and their deposition in tectonically alien basin (Mack,1984; Velbel,1985; Lucchi,1985),varying tectonic style at provenance and mixing from two or more sources (Mack,1984; Marsaglia and Ingersoll,1992), sediment recycling (Blatt,1967; Cox and Lowe,1995), sediment reworking in depositional environment (Espejo and Gamundi,1994) and diagenesis (McBride,1985). Hence it is necessary to synthesise and integrate all the above factors for the interpretations adduced from petrofacies study and in turn for logical identification of tectono-provenance.

In the present investigation, the detrital minerals of the Upper Bhander Sandstone were studied for the purpose of interpreting their tectonic provenance and plate tectonic setting. The present study is based on Dickinson (1985) classification.

CLASSIFICATION BASED ON DICKINSON'S (1985) SCHEME

Dickinson (1985) classified sandstone on the basis of their characteristic petrofacies, which is primarily controlled by the tectonic setting of their provenance. Using detrital modes of 105 sandstone suites which reflect different tectonic settings of provenance terrains, he grouped the provenance related to continental sources, into four major types: stable cratons, basement uplifts, magmatic arcs and recycled orogens.

In this study the detrital modes were recalculated to 100 percent as the sum of Qt, Qm, Qp, P, K, L, Lt, Lv and Ls (Table 10). The intrabasinal and detrital limeclasts (Lc) do not occur and heavy minerals were excluded.

Table 10. Classification and symbols of grain types (after Dickinson, 1985).

A. Quartzose Grain (Qt = Qm + Qp)

Qt = Total quartz grain.

Qm = Monocrystalline quartz.

Qp = Polycrystalline quartz.

B. Feldspar Grain (F = P+K)

F = Total feldspar grains.

P = Plagioclase grains.

K = K-Feldspar grains.

C. Unstable lithic fragments (L = Lv + Ls)

L = Total unstable lithic fragments.

Lv = Volcanic/ metasedimentary fragments.

Ls = Sedimentary/ metasedimentary fragments.

D. Total lithic fragments: (Lt = L + Qp)

Lc = Extrabasinal detrital lime clast (not included in L or Lt).

In this study four triangular diagrams, Qt-F-L, Qm-F-Lt, Qp-Lv-Ls and Qm-P-K were used (Table 11). Both Qt - F- L and Qm - F - Lt plots show full grain populations, but, with different emphasis. The Qt-F-L diagram emphasizing factors controlled by provenance, relief, weathering and transport mechanism as well as source rock, based on total quartzose, feldspathic and lithic modes. In this diagram, most of the studied sample data plot in the continental block provenance field and a few samples data lie in the recycled orogen provenance field (Figure 23) with a source primarily in the craton interior orogen and recycled orogen provenance with uplifted basement (Dickinson,1988).Global sandstone petrographic classifications show that petrofacies that plot within the recycled orogen provenance field are commonly derived from metasedimentary and sedimentary rocks that were originally deposited along former passive continental margins (Dickinson and Suczek, 1979; Dickinson, 1985).

Table 11. Percentage of framework modes of the Bhander Sandstone in parts of Uttar Pradesh - Rajasthan states. (Based on Dickinson's classification 1985).

Qt=Total quartz; Qm= Monocrystalline quartz; Qp= Polycrystalline quartz; F= Total feldspar grains; P= Plagioclase grains; K= K-Feldspar grains; L= Total unstable lithic fragments; Lv= Volcanic/ metavolcanic lithic fragments; Ls= Sedimentary/metasedimentary fragments; Lt: (L+Qp).

Sample No.	Qt	F	L	Qm	F	Lt	Qp	Lv	Ls	Qm	P	K
Rasulpur Section												
R1	93	5	2	92	5	3	33	0	67	95	2	3
R2	96	2	2	94	2	4	50	0	50	98	1	1
R3	97	2	1	92	2	6	83	0	17	98	1	1
R4	97	2	1	95	2	3	66	0	34	98	1	1
R5	99	0	1	97	0	3	66	0	34	100	0	0
R6	98	0	2	94	0	6	66	0	34	100	0	0
R7	96	3	1	90	3	7	86	0	14	97	1	2
R8	98	0	2	96	0	4	50	0	50	100	0	0
R9	97	1	2	91	1	8	75	0	25	99	1	0
R10	97	2	1	94	2	4	75	0	25	98	1	1
R11	98	0	2	97	0	3	25	0	75	100	0	0
R12	98	0	2	95	0	5	60	0	40	100	0	0
R13	98	0	2	96	0	4	50	0	50	100	0	0
Tehra Section												
T1	96	1	3	92	1	7	57	0	43	99	1	0
T3	97	2	1	93	2	5	80	0	20	98	0	2
T4	98	0	2	92	0	8	75	0	25	100	0	0
T5	96	2	2	91	2	7	71	0	29	98	1	1
T6	98	1	1	95	1	4	75	0	25	99	0	1
T7	99	0	1	91	0	9	89	0	11	100	0	0
T8	96	2	2	94	2	4	50	0	50	98	1	1
T9	96	2	2	92	2	6	67	0	33	98	1	1
T10	98	1	1	91	1	8	88	0	12	99	1	0

T11	96	2	2	93	2	5	60	0	40	98	1	1
T12	99	0	1	94	0	6	71	0	29	100	0	0
T13	96	2	2	91	2	7	83	0	17	98	1	1
Bakoli Section												
B1	95	3	2	90	3	7	71	0	29	97	2	1
B2	96	1	3	92	1	7	57	0	43	99	1	0
B3	96	2	2	89	2	9	78	0	22	98	1	1
B4	97	1	2	93	1	6	67	0	33	99	1	0
B5	95	3	2	90	3	7	71	0	29	97	2	1
Rupbas Section												
RP1	96	2	2	92	2	6	67	0	33	98	1	1
RP2	97	3	0	94	3	3	100	0	0	97	2	1
RP3	96	3	1	92	3	5	80	0	20	97	3	0
RP4	96	2	2	91	2	7	71	0	29	98	2	0
RP5	96	2	2	92	2	6	67	0	33	98	1	1
RP6	97	3	0	94	3	3	100	0	0	97	2	1
Gatouli Section												
GH1	95	3	2	92	3	5	60	0	40	97	2	1
GH2	94	4	2	90	4	6	67	0	33	96	1	3
GH3	93	6	1	93	6	1	0	0	100	94	4	2
GH4	96	3	1	91	3	6	83	0	17	97	1	2
GH5	95	4	1	92	4	4	50	0	50	96	2	2
GH6	94	3	3	93	3	4	25	0	75	97	1	2
Mewali Section												
M1	100	0	0	93	0	7	100	0	0	100	0	0
M2	96	2	2	89	2	9	78	0	22	98	1	1
M3	96	3	1	91	3	6	83	0	17	97	2	1
M4	99	0	1	91	0	9	89	0	11	100	0	0
M5	97	1	2	91	1	8	75	0	25	99	0	1
M6	96	3	1	91	3	6	83	0	17	97	1	2
M7	97	1	2	94	1	5	60	0	40	99	1	0
Jagnair Section												
J1	99	1	0	95	1	4	100	0	0	99	1	0

J2	99	0	1	96	0	4	75	0	25	100	0	0
J3	100	0	0	97	0	3	100	0	0	100	0	0
J4	97	1	2	93	1	6	67	0	33	99	1	0
J5	98	1	1	97	1	2	50	0	50	99	1	0
J7	94	3	3	92	3	5	25	0	75	97	1	2
Holipura Section												
HP1	95	4	1	92	4	4	75	0	25	96	4	0
HP2	95	2	3	92	2	6	50	0	50	98	2	0
HP3	99	0	1	97	0	3	75	0	25	100	0	0
Tantpur Section												
TT1	96	2	2	92	2	6	67	0	33	98	2	0
TT2	96	3	1	94	3	3	75	0	25	97	3	0
TT3	94	4	2	92	4	4	50	0	50	96	2	2
TT4	96	3	1	92	3	5	80	0	20	97	2	1
TT5	94	5	1	91	5	4	75	0	25	95	3	2
TT6	96	2	2	94	2	4	50	0	50	98	2	0
TT7	95	3	2	93	3	4	50	0	50	97	3	0
TT8	95	4	1	92	4	4	75	0	25	96	3	1
Baretha Section												
BD1	94	3	3	93	3	4	33	0	67	97	2	1
BD2	97	1	2	95	1	4	50	0	50	99	1	0
BD3	95	2	3	93	2	5	40	0	60	98	1	1
BD4	97	1	2	97	1	2	0	0	100	99	1	0
BD5	96	2	2	95	2	3	33	0	67	98	1	1
BD6	96	2	2	96	2	2	0	0	100	98	1	1
BD7	96	2	2	93	2	5	60	0	40	98	0	2
BD8	96	3	1	94	3	3	67	0	33	97	2	1
BD9	98	0	2	93	0	7	67	0	33	100	0	0
BD10	96	3	1	93	3	4	71	0	29	97	2	1
BD11	98	0	2	93	0	7	75	0	25	100	0	0
Gchadi Bajana Section												
G1	97	2	1	92	2	6	83	0	17	98	2	0
G2	96	2	2	93	2	7	71	0	29	98	2	0

G3	95	2	3	90	2	8	63	0	37	98	2	0
G4	96	2	2	90	2	8	75	0	25	98	2	0
G5	94	2	4	90	2	8	50	0	50	98	0	2
Bansi Paharpur Section												
BP1	94	3	3	91	3	6	50	0	50	97	2	1
BP2	95	2	3	93	2	5	25	0	75	98	1	1
BP3	95	4	1	93	4	3	75	0	25	96	2	2
BP4	95	3	2	91	3	6	67	0	33	97	2	1
BP5	94	4	2	90	4	6	67	0	33	96	2	2
BP6	94	3	3	88	3	9	67	0	33	97	3	0
BP7	95	3	2	92	3	5	60	0	40	97	1	2
BP8	95	2	3	90	2	8	63	0	37	98	2	0
BP9	94	3	3	89	3	8	63	0	37	97	1	2
BP10	97	1	2	90	1	9	78	0	22	99	0	1
BP11	96	2	2	91	2	7	71	0	29	98	1	1
BP12	95	3	2	92	3	5	60	0	40	97	2	1
BP13	94	3	3	90	3	7	57	0	43	97	2	1
Rudawal Section												
RD1	96	2	2	91	2	7	71	0	29	98	2	0
RD2	95	3	2	89	3	8	75	0	25	97	2	1
RD3	96	2	2	90	2	8	75	0	25	98	1	1
RD4	95	2	3	89	2	9	67	0	33	98	2	0
RD5	96	2	2	90	2	8	75	0	25	98	1	1
RD6	94	4	2	90	4	6	67	0	33	96	2	2
RD7	99	0	1	95	0	5	80	0	20	100	0	0
RD8	97	2	1	94	2	4	75	0	25	98	1	1
RD9	98	0	2	92	0	8	75	0	25	100	0	0
RD10	94	4	2	93	4	3	33	0	67	96	2	2
Average Area Level	96	2	2	92	2	6	65	0	35	98	1	1

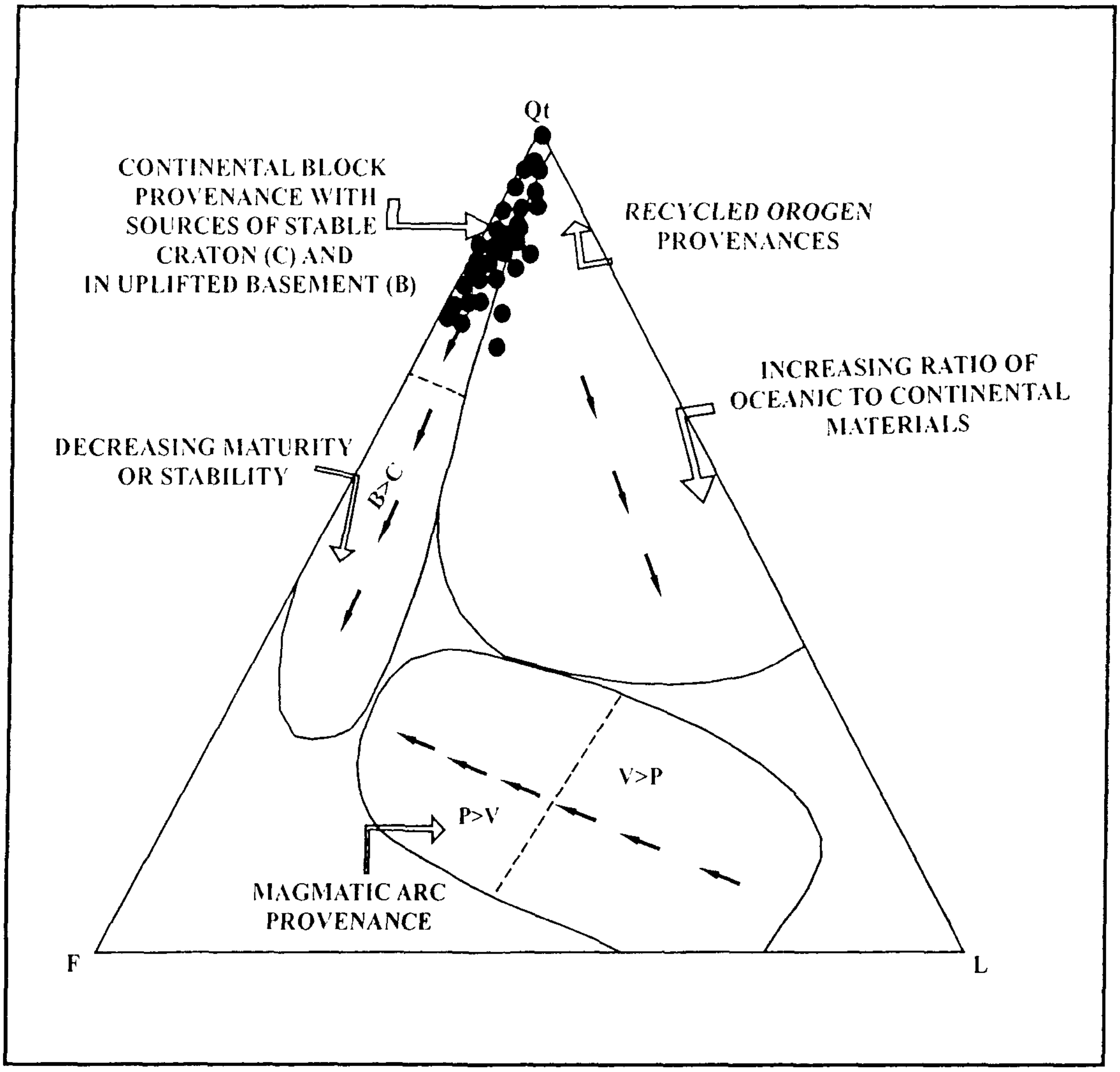


Figure 23. Classification of the Upper Bhander Sandstone, (according to Dickinson, 1985),Qt-F-L.

In the Qm-F-Lt diagram, all unstable lithic fragments including the polycrystalline quartz are plotted together as Lt, to emphasize the source rocks. In this diagram, most of the sample data plots in the recycled orogen provenance field, transitional zone and continental block provenance field (Figure 24). The ratio of monocrystalline quartz to that of polycrystalline quartz reflects the maturity of the sediments and sedimentary rocks because the amount of polycrystalline quartz tends to reduce by recycling and weathering (Basu, 1985). The Qp – Lv- Ls plot, which is based on rock fragment population reveals the poly-minerallic component of source region and gives a more resolved picture about the tectonic elements. The sample data plot in rifted continental margin basin setting and few in thrust belt setting only (Figure 25) reflecting no contribution from the volcanic source. The Qm – P-K plot of the data shows that all the sediment contribution is from the continental block basement uplift provenance (Figure 26) and is reflected in mineralogical maturity of the sediments.

Tectono- Provenance

Plutonic (common) quartz is the predominant mineral constituent in the Upper Bhander Sandstone. It is mainly derived from granitic batholiths or granitic gneisses. The recrystallised metamorphic quartz indicates an origin from metaquartzite, highly metamorphosed granite and gneissic rocks. The stretched metamorphic quartz was probably derived from granite, schist . Mica present in the studied sandstones comprises mainly muscovite and a few biotite grains derived probably from granite, pegmatite or schist.

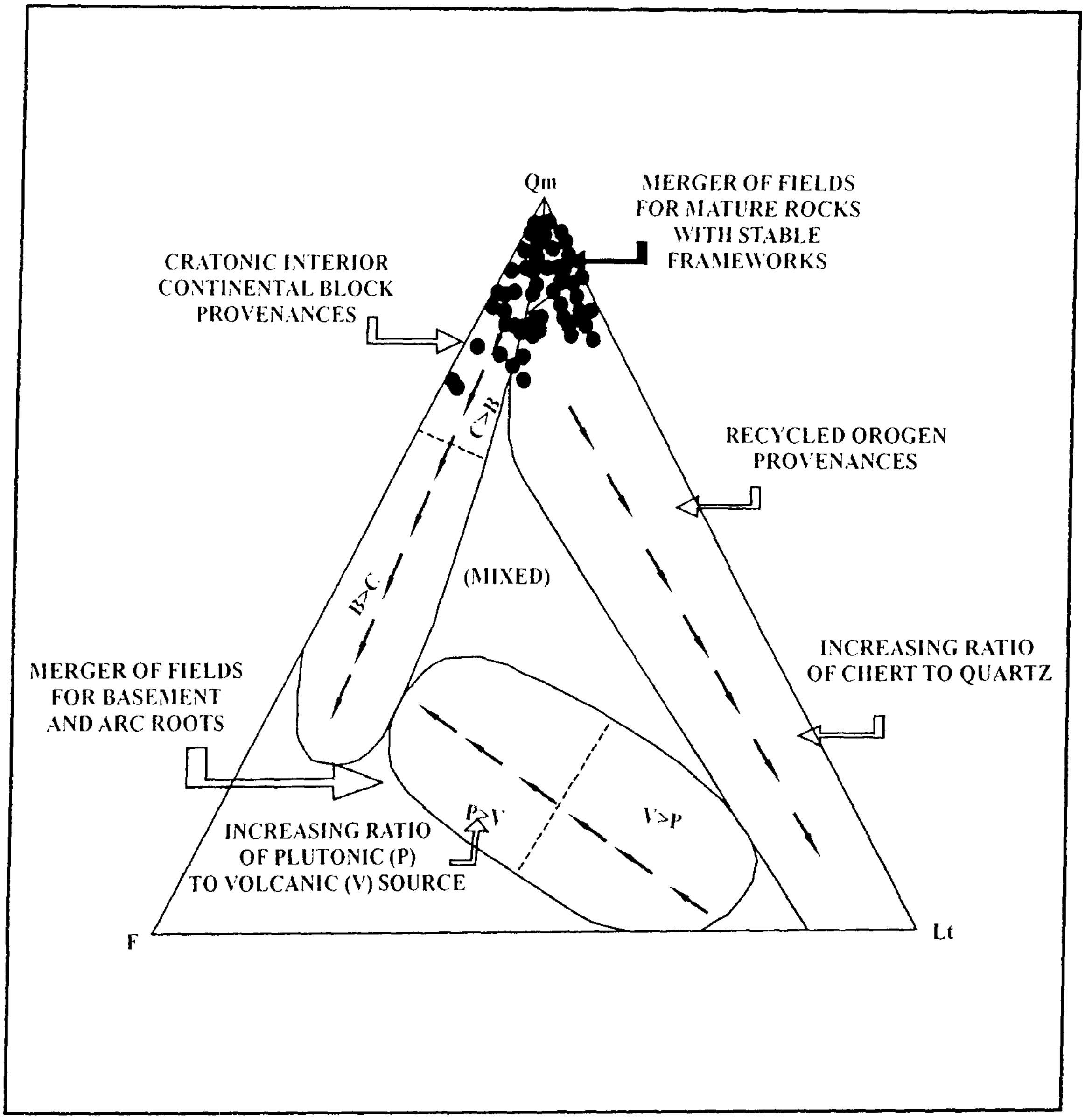


Figure 24. Classification of the Upper Bhander Sandstone, (according to Dickinson, 1985), Qm-F-Lt.

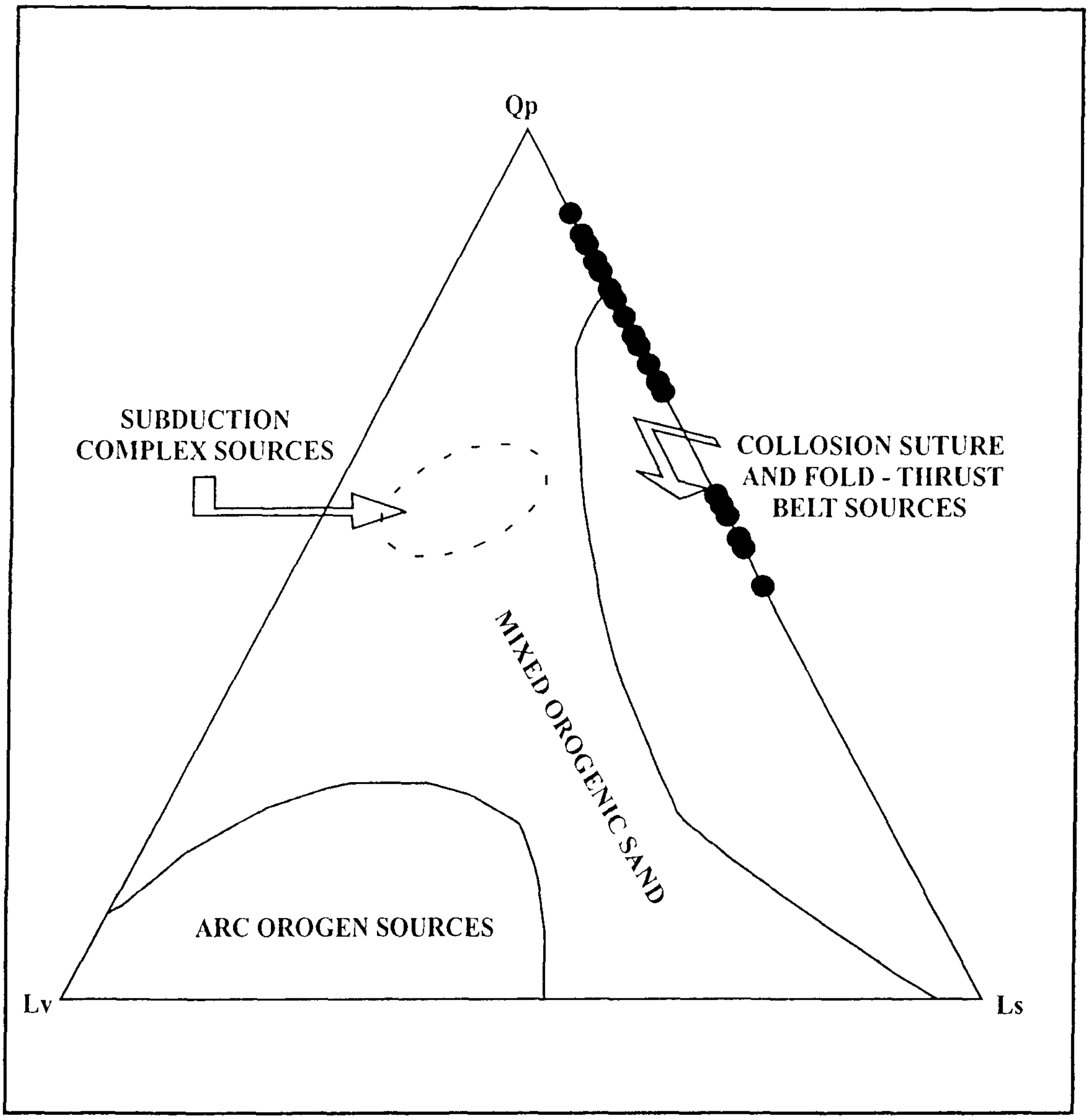


Figure 25. Classification of the Upper Bhander Sandstone, (according to Dickinson, 1985), Qp-Lv-Ls.

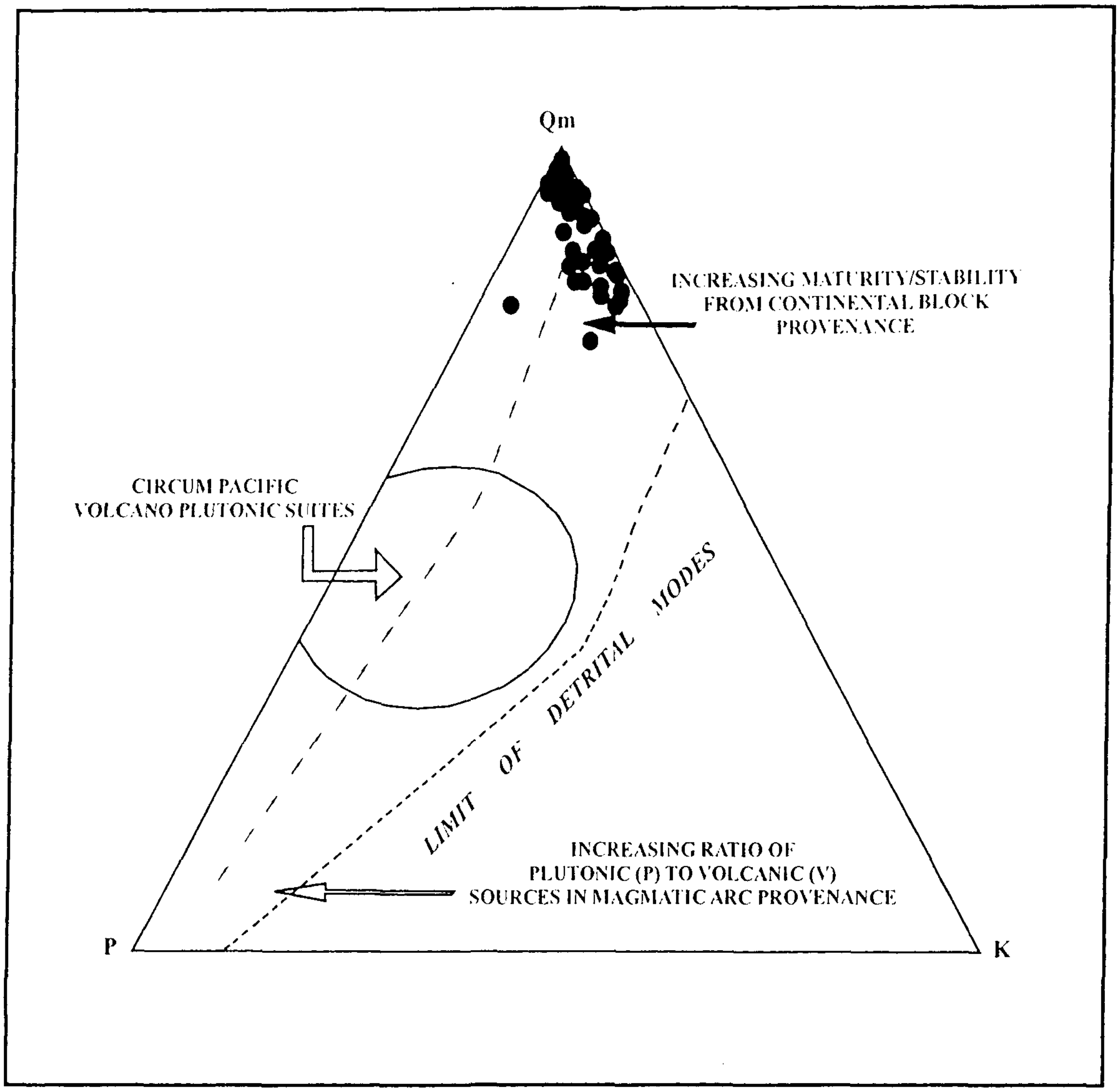


Figure 26 . Classification of the Upper Bhander Sandstone, (according to Dickinson, 1985), Qm-P-K.

The suite of heavy minerals with biotite, tourmaline and zircon indicate acid igneous source for these sediments. On the other hand the suite of heavy minerals including garnet and epidote reflects metamorphic source. Rounded to sub rounded grains of tourmaline, rutile and zircon is indicative of multicycled source for the sediments. Paleocurrent study indicates that during deposition of the Upper Bhander Sandstone, palaeoslope was towards NW, SW and NE, facing Precambrian metasediments and granite- gneisses of Delhi and Aravalli Supergroup. The petrofacies analysis of the Upper Bhander Sandstone indicates multiple rock sources for these sandstones which are not reflected in the triangular plots. The apparent reason for this could be diagenetic alteration and weathering of unstable framework grains and consequent increase in the proportion of quartz grains.

The data on the types of quartz are plotted on the provenance discrimination diagram of Basu et al., (1975) in Figure 27 and Table 12. The data plot in the plutonic and middle to high rank metamorphic fields with almost equal contribution from either. This plot yields consistent result that indicates a source area containing largely of plutonic and upper metamorphic rocks, which represent the exposed roots of magmatic cores or older crystalline basement in the area (Dickinson and Suczek, 1979).

The plots of the Upper Bhander Sandstone on Qt-F-L and Qm-F-Lt diagrams suggest that the detritus of the sandstones were derived from the granite-gneisses exhumed in the craton interior and medium to high grade metamorphic supracrustals forming recycled orogen provenance.

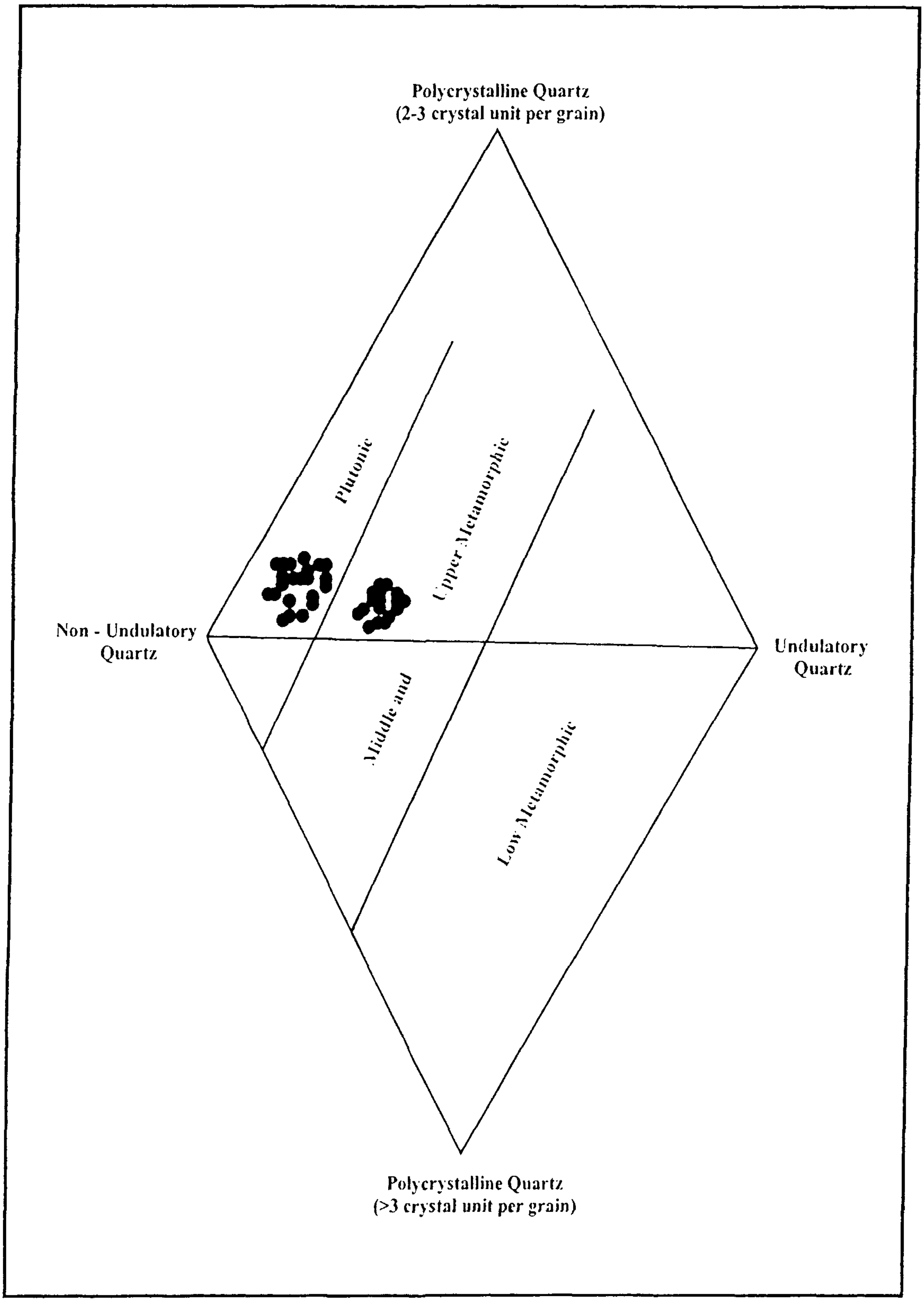


Figure 27. Diamond diagram of the Upper Bhander Sandstone (after Basu et al.,1975)

Table 12. Types of Quartz of the Upper Bhander Sandstone in parts of Uttar Pradesh - Rajasthan States.

Sample No.	Non-undulatory Monocrystalline Quartz	Undulatory Monocrystalline Quartz	Polycrystalline Quartz	
			2-3 crystals	>3 crystals
Rasulpur Section				
R1	69	27	4	-
R2	79	14	7	-
R3	86	11	3	-
R4	81	15	4	-
R5	76	15	6	3
R6	74	13	8	5
R7	78	14	3	5
R8	84	10	6	-
R9	91	6	3	-
R10	80	10	10	-
R11	83	13	4	-
R12	70	24	6	-
R13	90	6	4	-
Tehra Section				
T1	83	9	3	5
T3	74	13	8	5
T4	78	14	3	5
T5	84	10	6	-
T6	91	6	3	-
T7	70	26	4	-
T8	80	17	3	-
T9	70	26	4	-
T10	80	12	5	3
T11	77	13	7	3
T12	80	15	2	3
T13	78	13	6	3

Bakoli Section				
B1	73	17	6	4
B2	67	24	9	-
B3	68	24	8	-
B4	79	14	5	2
B5	81	10	6	3
Rupbas Section				
RP1	78	14	3	5
RP2	84	10	6	-
RP3	91	6	3	-
RP4	80	10	10	-
RP5	83	13	4	-
RP6	70	24	6	-
Gatouli Section				
GH1	90	6	4	-
GH2	71	25	4	-
GH3	79	12	5	4
GH4	82	8	6	4
GH5	80	16	4	-
GH6	81	14	5	-
Mewali Section				
M1	75	15	8	2
M2	79	14	5	2
M3	79	12	5	4
M4	82	8	6	4
M5	78	15	7	-
M6	84	11	5	-
M7	85	10	5	-
Jagnair Section				
J1	82	10	5	3
J2	77	14	6	3
J3	74	13	8	5

J4	64	27	9	-
J5	70	21	9	-
J7	72	21	7	-
Holipura Section				
HP1	80	15	5	-
HP2	72	23	5	-
HP3	78	16	6	-
Tantpur Section				
TT1	74	20	6	-
TT2	78	15	7	-
TT3	84	11	5	-
TT4	85	10	5	-
TT5	87	7	6	-
TT6	78	16	6	-
TT7	83	13	3	1
TT8	80	12	6	2
Baretha Section				
BD1	87	10	3	-
BD2	81	12	7	-
BD3	70	20	10	-
BD4	88	8	4	-
BD5	87	10	3	-
BD6	81	12	7	-
BD7	70	20	10	-
BD8	88	8	4	-
BD9	83	13	4	-
BD10	70	20	10	-
BD11	88	8	4	-
Gchadi Bajana Section				
G1	84	11	5	-
G2	83	10	7	-
G3	81	10	6	3
G4	78	12	5	3

G5	77	10	7	3
Bansi Paharpur Section				
BP1	81	10	6	3
BP2	80	12	5	3
BP3	77	13	7	3
BP4	80	15	2	3
BP5	78	13	6	3
BP6	78	14	3	5
BP7	84	10	6	-
BP8	91	6	3	-
BP9	80	10	10	-
BP10	83	13	4	-
BP11	70	24	6	-
BP12	90	6	4	-
BP13	71	25	4	-
Rudawal Section				
RD1	80	15	2	3
RD2	78	13	6	3
RD3	82	10	5	3
RD4	76	15	6	3
RD5	84	11	5	-
RD6	83	10	7	-
RD7	80	15	5	-
RD8	72	23	5	-
RD9	78	16	6	-
RD10	74	20	6	-
Average Area Level	80	14	5	1

The sediments were deposited in intracratonic rift basin conditions as evidenced from Qp-Lv-Ls diagrams. The Qm-P-K plot of the data shows that all the sediment contribution is from the continental-block basement uplift provenance and is reflected in mineralogical maturity of the sediments. The relative abundance of monocrystalline quartz to that of polycrystalline quartz appears to reflect the maturity of the sediments, because polycrystalline quartz is eliminated by recycling and disintegrates in the zone of weathering as does strained quartz (Basu, 1985). The sandstones have considerably high percentage of monocrystalline quartz (90.98%) as compared to polycrystalline quartz (1.82%), which indicates removal of polycrystalline quartz by weathering and recycling. Abundance of feldspar also serves as a guide to determine the maturity index since much of the feldspar is destroyed by weathering where relief is low and rainfall high. Generally a small percentage of feldspar in the sandstone suggests that they were lost in the soil profile or by abrasion during transit or lost by solution during diagenesis. However, occurrence of weathered and fresh feldspars together indicates derivation from two different sources.

The Vindhyan Basin facing Delhi-Satpura mobile belt developed on the subducted Bundelkhand Protocontinent, following its collision with the southern Protocontinent in the middle Proterozoic. The basin, thus, developed as a post- orogenic intracratonic trough similar to a peripheral foreland basin, following the Delhi-Satpura orogeny. The Vindhyan Basin was formed largely through rift-controlled subsidence under extensional regime and locally by downward flexuring of the basement near tectonic margins. The depositional environment of Vindhyan Basin have been interpreted as shallow marine, coastal plain, lagoon through fluvio-deltaic to fluvial, depending upon basin profile and position of shoreline, which progressively retreated northward through time (Bose et al., 1988; Chakraborty, 1999;Casshyap et al., 2001; Sarkar et al., 2002;Gupta et al., 2003; Banerjee and Jeevankumar, 2007; Sarkar et al., 2008;). The original basin possibly extended beyond the existing tectonic boundaries to the south and west. The sediments of the extended basin are no longer exposed/preserved due to subsequent widespread thrusting and erosion with a few exceptions like the occurence of basal Vindhyan rocks of Jungel outlier in the Mahakoshal (Bijawar) belt of son valley. Recent observations on tectonics of Son Valley support the contention of possible extension of Vindhyan basin on the Satpura-Bijawar basement beyond the existing boundary in the south (Ravi Shankar, 1993). The predominant carbonate facies including basal conglomerate and sandstone of the lower Vindhyan is progressively replaced by shale and sandstone in the upper part. The Upper Vindhyan abounds in clastics, with increased development of sandstone towards the Bhander Group. It is believed that there were two separate basins divided by Bundelkhand massif during the deposition of Semri Group (Soni et al., 1987) but quiet likely the basin was unified during the deposition of Upper Vindhyan. Based on consistency of Palaeocurrent data across the basin, it is inferred that the clastic sediments of Lower and Upper Vindhyan were derived largely from the Satpura-Bijawar highlands to the south, locally from

Bundelkhand massif lying in the north, and Delhi-Aravalli fold belts in the west (Raza and Casshyap, 1994). The tectonic setting of the Vindhyan basin is seemingly akin to that of the Indus-Ganga and Alpine basins, both located on subducting plate and cited as example of peripheral foreland (Dickinson, 1974; Reading, 1986), foredeep (Miall, 1984,2000; Paikaray et al.,2008) basin.

The sedimentary fill and stable setting of the Vindhyan Basin are 'however', unlike those of the aforesaid foreland basins overlooking the rising fold belts of high relief, in which thick terrigenous sediments mainly comprising polymictic coarse clastics are deposited at a rapid rate. However, paucity of coarse and polymict clasts and dominance of quartzarenite and good textural maturity in the basal part of Vindhyan Supergroup (i.e., Semri Group) suggest that the highlands providing the sediment debris to the peripheral basin were reduced to low relief due to protracted erosion of the uplifted fold belt. This discrepancy in the post orogenic Vindhyan basin is inexplicable, pending relevant data in respect of the original deposition and abundance of sandstone and conglomerate facies and basement deepening (fleuxuring) in the basal/ proximal parts. Dominance of quartzarenite and good textural maturity in the Upper Bhander Sandstone suggest that the highlands formed by uplifted fold belts provided sediment debris to low relief area through their protracted erosion.

CHAPTER VII

DIAGENESIS

Those constituents which have been formed within the sediments by subsequent changes are called authigenic constituents, "Authigenic is to some extent synonymous to diagenetic". Diagenesis includes "all physicochemical, biochemical and physical processes modifying sediments between deposition and lithification at low temperature and pressure, characteristics of surface and near- surface environments" (Chilingar et al., 1967). The principal diagenetic processes include compaction, cementation, authigenesis, recrystallisation, replacement and metasomatism. Diagenesis in clastic rocks is governed by many factors such as mineralogy, temperature, pressure, water composition, flow rates, dissolution and precipitation kinetics, availability of nucleation sites, porosity and permeability. Freshly deposited sand is a porous, non equilibrium mixture of detrital minerals. This is achieved by reduction of porosity through compaction and precipitation of stable authigenic cements or grains.

Diagenesis is locally, controlled by the migration of fluids and chemical potential of the system. On a regional scale, tectonic setting of the basin, geothermal gradient, rate and extent of deposition and basin subsidence play a significant role. For sandstone, the processes can be classified into two broad categories- physical and chemical diagenesis. Both these processes may operate independently, in random or simultaneously in response to the surrounding stress field in order to achieve chemical equilibrium.

The physical diagenesis of the freshly deposited sand results in compaction of the sediments and pore volume reduction due to pressure. At the sediment water interface and at shallow level of burial, physical compaction takes place by the process of grain rearrangement by rotation, slippage, ductile deformation and grain fracturing without dissolution at grain contacts (Houseknecht, 1987). Continued physical compaction results in the increase in number of contacts per grain, which passes into a regime of chemical compaction characterised by intergranular pressure solution, after considerable depth of burial. The increased geothermal gradient and pressure results in dissolution of grain contacts and change their nature from point to long and interpenetrative contacts.

The chemical diagenesis includes reaction leading to chemical dissolution, corrosion and cementation. These reactions may start just after the deposition of sand and are controlled by oxidation and reduction at sediment water/ atmosphere interface. Chemical potential of sediments and pore water chemistry play an important role in the removal of various unstable phases and precipitation of new stable phases in diagenetic regime. The process of cementation results in loss of porosity as it occludes the pore spaces but is reversible in contrast to loss by compaction, which is irreversible. The cementing material may be carbonate, silica, iron oxide or clay minerals. The cementation process leads towards the precipitation of new minerals on the grains and into the voids from the pore fluids (saturated with silica, iron oxide or clay). The minerals get precipitated under suitable physico- chemical conditions.

The present study on diagenesis of the Upper Bhander Sandstone mainly focuses on compaction, porosity reduction and cementation. Compaction is the process of volume reduction expressed either as a percentage of the original voids present or of the original bulk volume. Although compaction affects mainly loose, unlithified sediments, the process may also have profound influence on well cemented deposits as indicated by stylolithic contacts. The intergranular pore spaces of clastic sediments are eliminated by closer packing, crushing deformation, expulsion of fluids and possibly, dissolving of grains. The rate of compaction and the decrease in porosity and permeability, as well as the rate of expulsion of fluids are believed to change with time, both vertically and horizontally in sedimentary basins.

The chemical precipitation of cements in the framework of sedimentary deposits is dependent on a supply of chemical elements by intrastratal solutions, usually moving solutions. An understanding of the process of compaction and lithification is required in the study of diagenesis in order to determine the direct influence of compaction and cementation as well as the time relationship between compaction and lithification.

METHODOLOGY

The present study is based on 105 sandstone samples which were cut into standard petrographic thin sections. 200 to 250 grains were counted per thin section. Standard petrological techniques using a polarizing microscope were employed to describe the thin sections. Authigenic components (cement and matrix replacement constituents) were counted separately. In order to reconstruct the original detrital composition of the sandstones, the effects for diagenesis were taken into consideration as much as possible during counting. Taylor's (1950) method was applied for the study of the nature of detrital grain contacts and for computation of contact index, the method that of Pettijohn et al., (1987) was used.

COMPACTION

Compaction, which is the one of the main processes of diagenesis, can be defined as the expulsion of pore fluids and pore volume decrease in sedimentary column as a result of normal shear compressional stresses due to the overburden load (Chilingar, 1983). Compaction occurs in response to four types of processes grain rearrangements, plastic deformation, dissolution and brittle deformation (Wilson and Staton, 1994). Compaction of sediments which is the process of volume reduction can be expressed as a percentage of original voids presents.

Grain contact

A grain to grain contact of sediments gives an idea about pore space reduction and compaction history of the sediments. The nature of contacts and contact index are helpful in understanding the aggregate packing of the rocks. Grain contacts of the Upper Bhander Sandstone were studied in thin sections with a view to interpret the compactional history of the formation. In the present study the closely packed sandstone exhibit four types of grain contacts (Taylor, 1950), which include point, long (line contact), concavo-convex and sutured contacts. The observed number of various types of grain contacts in different samples is given in Table 13 and

Table 13. Packing data for the Upper Bhander Sandstone in parts of Uttar Pradesh - Rajasthan States.
F= Floating grains, P= Point contact, L= Long contact, Cc= Concavo-convex contact, S= Sutured contact, C.I= Contact Index.

Sample No.	Types of contact										Number of grains in Contact														Contact Index
	F		P		L		Cc		S		0		1		2		3		4		>4				
	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%			
Rasulpur Section																									
R1	12	16	9	12	45	68	-	-	11	4	16	10	40	25	63	40	34	22	4	2	1	1			2.3
R2	26	33	10	13	36	52	-		8	2	18	20	20	21	34	37	20	22	-	-	-	-			2.1
R3	8	18	4	9	29	71	-	-	4	1	-	-	28	29	40	42	25	26	2	3	-	-			2.5
R4	8	18	6	21	25	57	-	-	5	2	7	6	27	24	39	35	38	34	4	1	-	-			2.62
R5	7	21	5	15	17	58	-	-	4	2	12	10	45	39	32	28	20	17	5	4	1	2			2.15
R6	10	21	6	13	24	57	2	3	6	4	14	13	25	23	35	32	25	23	7	6	2	3			2.63
R7	2	5	14	32	23	54	-	-	5	4	14	11	24	20	45	38	32	27	2	2	2	2			2.39
R8	4	9	10	22	26	63	1	4	4	3	19	17	52	28	75	41	27	13	1	1	-	-			2.13
R9	15	22	21	31	27	38	-		4	1	15	12	40	31	47	36	25	14	1	5	2	2			2.2
R10	6	8	25	39	36	57	-	-	8	2	35	18	60	33	70	39	15	10	-	-	-	-			1.85
R11	-	-	21	31	36	56	-	-	10	1	20	13	70	44	55	34	15	9	-	-	-	-			2.31
R12	3	3	35	33	63	59	-	-	4	1	5	3	42	26	65	40	35	22	15	9	-	-			2.28
R13	4	5	22	25	51	67	-	-	10	2	10	7	50	34	70	48	15	10	2	1	-	-			2.14

Tehra Section																						
T1	25	32	8	10	40	50	2	3	6	2	15	10	30	20	45	31	55	37	1	1	1	1	2.49
T3	30	32	3	3	49	56	2	1	11	1	5	3	25	17	50	34	65	45	1	1	-	-	2.71
T5	7	11	5	8	40	72	3	2	10	4	2	26	30	25	55	44	25	15	-	-	-	-	2.40
T6	40	59	5	7	20	30	2	1	1	2	35	54	15	23	10	15	5	8	-	-	-	-	1.48
T7	25	29	10	12	45	52	1	1	5	1	5	4	20	15	55	42	45	34	7	5	-	-	2.69
T8	40	51	13	17	19	26	1	2	5	5	40	42	20	21	35	37	-	-	-	-	-	-	1.44
T9	20	27	8	11	40	55	-	-	5	3	25	24	35	33	40	38	5	5	-	-	-	-	1.7
T10	29	27	15	14	50	56	2	4	10	2	10	10	25	26	45	47	15	16	1	1	-	-	2.91
T11	26	31	7	8	45	54	1	2	5	1	15	12	30	25	50	41	25	21	1	1	-	-	2.21
T12	25	25	15	15	50	56	2	1	7	4	30	24	25	20	30	26	2	29	1	1	-	-	1.56
T13	17	17	20	19	55	62	1	4	10	2	10	12	20	22	45	49	15	16	1	1	-	-	2.21
T14	20	21	15	16	50	58	2	1	7	1	15	13	25	23	50	43	20	17	5	4	-	-	1.95
Bakoli Section																						
B1	2	3	13	19	45	75	-	-	7	3	25	19	50	38	40	30	15	11	2	2	-	-	1.86
B2	10	22	6	13	24	60	-		5	2	25	27	50	38	40	31	5	4	-	-	-	-	1.55
B3	4	5	18	23	50	67	-	-	5	2	27	20	35	26	45	40	15	11	5	3	-	-	1.83
B4	3	4	18	26	41	64	3	1	4	2	15	11	40	30	55	41	20	15	4	3	-	-	2.14
B5	6	8	20	26	48	62	-	-	2	3	10	8	35	30	45	38	25	21	2	2	1	1	2.66
Rupbas Section																						
RP1	20	16	35	27	62	59	-	-	2	4	5	5	30	26	50	45	15	14	9	10	-	-	2.39
RP2	15	10	40	29	75	55	-		10	1	10	16	15	23	25	38	10	15	5	8	-	-	2.23

RP3	25	25	30	29	42	39	-	-	5	2	15	19	20	25	35	43	10	12	1	1	-	-	2.02
RP4	15	10	40	29	75	55	-	-	10	2	10	16	15	23	25	38	10	15	5	8	-	-	2.23
RP5	25	25	30	29	42	39	-	-	5	3	15	19	20	25	35	43	10	12	1	1	-	-	2.02
RP6	20	16	35	27	55	50	7	3	12	4	5	5	30	27	50	45	15	14	9	10	-	-	2.39
Gatouli Section																							
GH1	30	27	20	18	55	49	3	1	5	4	10	9	35	30	45	39	25	21	1	1	-	-	2.23
GH2	20	16	30	24	60	53	-	-	15	2	10	9	15	14	25	33	44	42	2	2	-	-	2.36
GH3	10	7	40	27	65	63	15	1	20	1	5	12	20	16	40	33	45	37	3	2	-	-	2.67
GH4	40	57	5	7	20	29	2	2	3	5	10	16	15	21	24	35	19	28	1	2	-	-	2.3
GH5	20	16	30	25	65	53	-	-	7	3	15	26	20	19	40	40	15	14	2	1	-	-	2.14
GH6	15	15	80	20	50	58	5	4	8	3	25	20	30	40	20	25	10	14	1	1	-	-	1.69
Mewali Section																							
M1	15	18	20	24	42	55	-	-	3	1	2	2	15	13	55	47	35	30	10	8	-	-	2.79
M2	20	22	17	18	52	56	-	-	3	3	21	24	25	27	45	49	-	-	-	-	-	-	1.75
M3	25	27	15	16	40	52	5	1	4	2	5	4	35	25	46	51	15	12	10	8	-	-	2.30
M4	30	26	17	15	55	52	7	1	3	4	6	6	25	25	45	44	25	25	-	-	-	-	2.36
M5	20	23	15	17	45	54	3	1	3	3	2	1	30	28	40	36	35	31	5	4	-	-	2.59
M6	15	16	20	22	49	57	-	-	3	3	3	2	35	23	45	29	65	41	5	3	-	-	2.7
M7	10	11	25	27	55	58	-	-	2	2	-	-	25	19	55	39	45	32	6	4	-	-	2.72
Jagnair Section																							
J1	5	5	20	20	50	69	10	1	15	4	3	10	20	11	45	25	75	43	15	8	5	3	2.78
J2	25	29	15	17	40	46	2	1	5	2	30	27	45	40	20	18	5	13	2	2	-	-	1.54

J3	10	9	15	13	60	71	10	1	17	1	15	12	20	16	45	36	35	28	10	8	-	-	2.54
J4	25	25	15	16	40	57	8	1	10	2	5	4	15	11	55	39	65	45	2	1	-	-	2.79
J5	30	29	10	10	55	55	-	-	7	3	10	10	20	17	45	37	35	28	10	8	-	-	2.6
J7	25	29	7	8	40	57	3	2	10	3	15	10	25	17	46	32	55	38	4	3	-	-	2.53
Holipura Section																							
HP1	5	5	20	20	50	69	10	1	15	2	25	9	30	38	20	27	10	14	1	2	-	-	1.69
HP2	30	46	5	8	15	39	5	1	10	3	65	78	15	19	1	1	1	1	1	1	-	-	0.78
HP3	20	27	7	9	40	57	2	1	5	1	45	44	25	24	20	30	1	1	1	1	-	-	1.14
Tantpur Section																							
TT1	15	12	30	29	60	55	8	1	10	1	2	2	20	18	55	49	30	27	5	4			2.62
TT2	5	5	55	30	65	56	3	1	7	4	1	1	30	21	75	53	25	18	10	7			2.58
TT3	7	8	25	25	50	61	5	1	10	2	10	9	25	23	55	50	15	14	5	4			2.3
TT4	15	13	30	25	60	50	5	1	10	1	20	21	15	17	33	39	20	22	1	1			2.11
TT5	17	13	33	25	66	49	7	2	11	2	10	11	20	22	43	48	15	17	2	2			2.25
TT6	25	16	40	26	75	48	-	-	10	3	20	41	10	20	15	31	3	6	1	2			1.56
TT7	15	9	45	28	75	50	7	1	12	2	10	13	25	32	35	45	5	6	3	4			2.05
TT8	10	9	35	32	55	49	4	2	7	1	12	12	30	30	45	45	10	10	3	3			2.11
Baretha Section																							
BD1	20	17	30	26	55	53	2	1	10	2	20	40	15	30	10	20	5	10	-	-	-	-	1.5
BD2	15	12	30	24	65	52	5	2	10	1	5	7	25	37	35	53	2	3	-	-	-	-	1.99
BD3	15	12	35	29	65	53	2	2	5	4	2	2	45	42	35	33	25	23	-	-	-	-	2.26
BD4	15	11	35	27	70	53	5	1	7	2	1	1	25	22	44	40	35	32	5	5	-	-	2.66

BD5	25	19	30	23	66	50	3	1	7	1	1	2	16	15	44	50	25	27	6	6	-	-	2.72
BD6	20	16	30	24	65	51	2	1	10	3	2	2	44	51	25	29	15	17	1	1	-	-	2.12
BD7	25	19	30	23	66	50	3	1	7	2	1	2	16	15	44	50	25	27	6	6	-	-	2.72
BD8	43	50	20	22	24	28	1	1	2	3	10	11	21	24	33	36	15	27	2	2	-	-	1.95
BD9	20	15	35	26	65	48	5	2	10	1	2	2	35	30	44	38	25	21	10	9	-	-	2.53
BD10	25	21	30	25	55	45	2	1	10	1	10	13	45	59	15	20	5	7	1	1	-	-	1.71
BD11	25	17	30	20	75	52	2	1	15	2	5	5	25	23	45	41	30	27	4	4	-	-	2.56
Ghadi Bajana Section																							
G1	20	15	35	27	65	49	2	1	10	4	10	12	15	18	35	41	25	29	-	-	-	-	2.35
G2	15	12	30	23	75	58	3	2	7	2	5	5	20	19	33	32	45	44	-	-	-	-	2.63
G3	15	13	25	21	65	54	5	1	10	1	12	16	15	19	45	58	5	7	-	-	-	-	2.04
G4	25	21	30	25	55	46	3	1	7	3	5	5	25	24	55	53	15	14	4	4	-	-	2.37
G5	20	15	35	26	66	49	4	1	10	3	4	3	22	19	45	39	35	30	10	9	-	-	2.68
Bansi Paharpur Section																							
BP1	25	23	20	19	50	47	2	1	10	1	1	1	35	35	45	45	15	15	4	4	-	-	2.35
BP2	15	15	25	25	55	54	1	2	5	2	5	5	20	23	25	27	35	38	6	7	-	-	2.65
BP3	25	18	30	21	70	49	-	-	15	2	10	10	21	20	45	43	25	24	4	3	-	-	2.41
BP4	80	81	5	5	10	10	3	2	1	2	30	54	15	27	10	19	-	-	-	-	-	-	1.12
BP5	65	78	9	11	5	7	2	2	2	1	35	56	10	17	15	24	2	3	-	-	-	-	1.23
BP6	15	12	30	24	65	52	5	1	10	2	15	15	35	35	45	45	5	5	-	-	-	-	1.88
BP7	20	17	35	30	50	42	4	1	9	4	20	19	45	43	25	24	15	14	-	-	-	-	1.82
BP8	25	23	20	19	50	47	2	1	10	2	40	42	20	21	35	37	-	-	-	-	-	-	1.44

BP9	20	17	30	25	60	51	3	1	5	1	25	24	30	28	45	43	5	5	-	-	-	-	1.76
BP10	15	12	30	24	65	53	4	2	10	2	15	12	30	25	55	45	20	16	2	2	-	-	2.18
BP11	30	25	25	21	55	42	-	-	10	2	27	36	33	44	10	13	5	7	-	-	-	-	1.4
BP12	35	30	25	22	50	35	5	2	10	2	10	13	25	33	35	46	6	8	-	-	-	-	1.97
BP13	25	19	30	23	62	46	-	-	15	2	15	19	35	44	20	25	10	12	-	-	-	-	1.79
Rudawal Section																							
RD1	10	8	25	21	65	64	5	1	15	1	-	-	21	16	55	42	35	27	15	11	5	4	2.92
RD2	15	11	30	22	75	56	6	1	10	4	-	-	35	27	57	43	30	23	10	7	-	-	2.59
RD3	25	26	15	16	35	46	5	2	16	2	2	3	15	19	35	46	25	32	-	-	-	-	2.56
RD4	15	12	30	24	65	59	7	1	10	1	-	-	25	23	45	42	30	28	5	5	2	2	2.69
RD5	25	22	30	27	50	46	2	1	3	3	45	75	10	17	5	8	-	-	-	-	-	-	0.82
RD6	15	13	30	25	65	55	3	2	5	4	-	-	15	14	55	46	35	29	10	8	4	3	2.81
RD7	10	8	20	20	60	69	5	1	7	3	-	-	25	29	45	52	15	17	2	2	-	-	2.42
RD8	20	15	30	23	65	55	5	2	10	1	30	39	15	27	35	13	10	21	-	-	-	-	2.09
RD9	25	20	30	25	50	49	7	1	10	1	45	52	35	40	5	6	2	2	-	-	-	-	1.07
RD10	20	15	35	26	60	51	6	2	15	4	-	-	25	21	45	38	35	29	10	8	5	4	2.86
Average Area Level		20		23		54		1		2													2.16

histogram constructed on the basis of grain contact data is shown in Figure 28. In loosely packed sandstone some grains may not make any contact with other grains, such grains are referred to as floating grains (F). The average percentage of different types of contacts in the studied sandstones is as follows: point contact (23 percent), Long contact (54 percent), concavo-convex contact (1 percent), sutured contact (2 percent) and floating grains (20 percent) (Table 13).

The dominance of point and long contacts, collectively averaging at 70 percent in the Upper Bhander Sandstone, indicates that the detrital grains were not subjected to large pressure solution, as a result of either shallow burial or early cementation. The pressure effects are absent or at minimum in sandstones which have undergone early cementation (Taylor, 1950). However, evidences of mechanical compaction and pressure solution do exist in the Upper Bhander Sandstone. Presence of sutured boundaries of quartz overgrowth indicates the post cement compaction. Therefore it may be concluded that some compaction of the Upper Bhander Sandstone took place in the early stages, when grains rotated and adjusted themselves to the boundaries of adjacent grains. Later compaction took place after cementation.

The contact index (CI), i.e., average number of the grain contacts a grain has with its neighboring grains (Pettijohn et al, 1987), also gives an indication about the degree of compaction of the sediments. Most of the grains are in contact with 2 grains followed by three grains. The average contact index of the Upper Bhander Sandstone is as high as 2.16 (Table 13). This is due to the dominance of long and point contacts in the framework constituent (Plate VIIA).

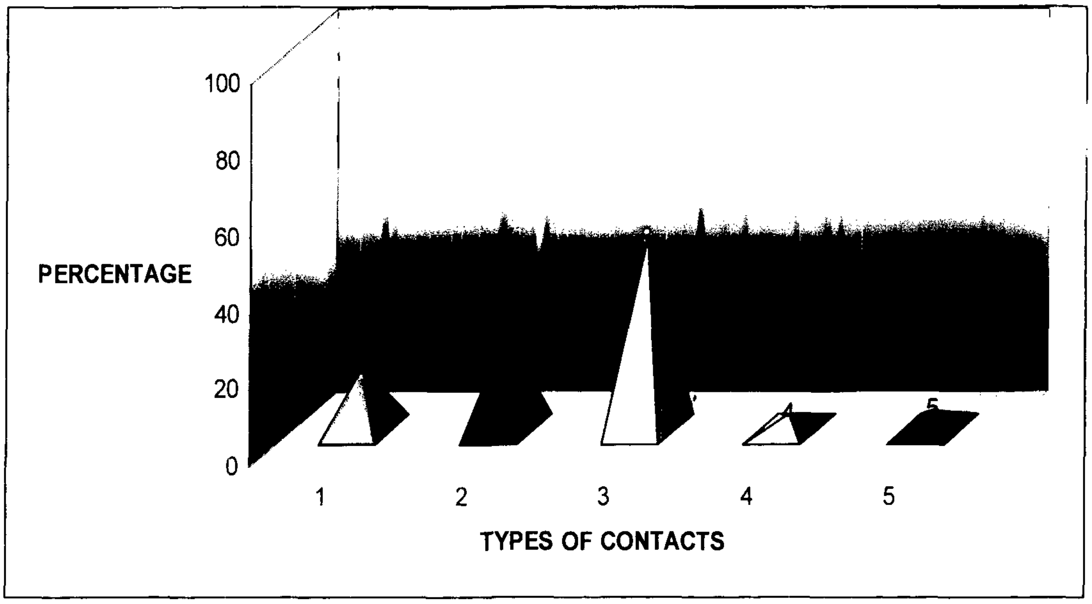


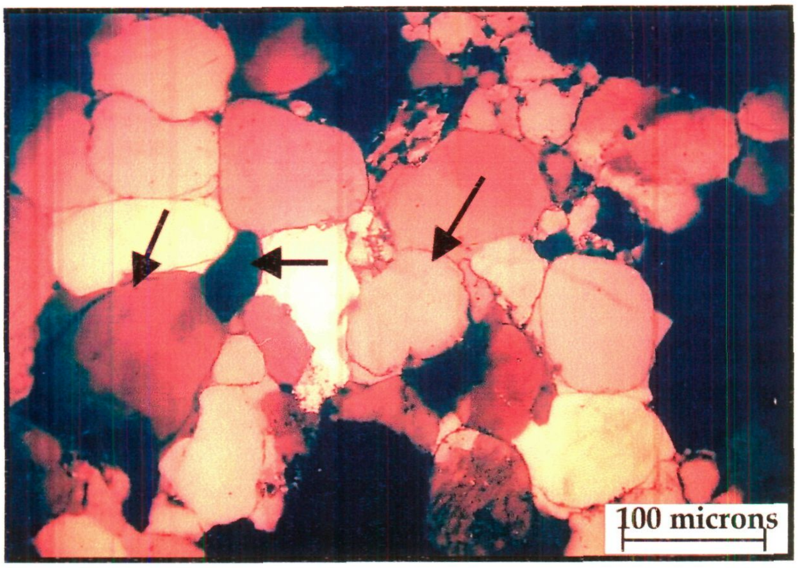
Figure 28. Histogram showing types of grain contacts of the Upper Bhander Sandstone in parts of Uttar Pradesh and Rajasthan States. 1= Floating grains, 2= Point contact, 3= Long contact, 4= Concavo-convex contact, 5=Sutured contact.

Dominance of long and point contact is attributed to mechanical compaction which increases the value of contact index and packing density. The chemical compaction involves pressure dissolution of grains along their contacts. This dissolution results in further increase in framework packing density and induces change in the nature of contacts e.g., changes from point and long contacts to sutured contact through concavo-convex contacts (Plate VII B,C).

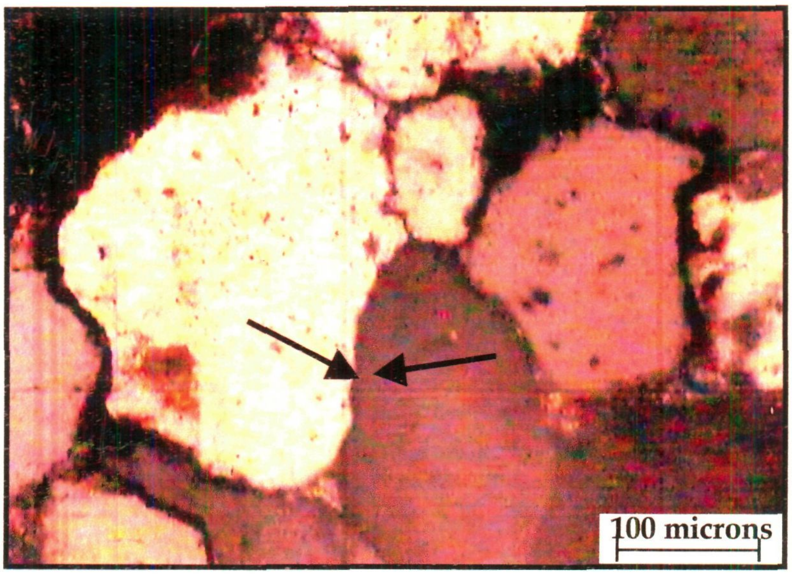
Porosity Reduction

The original porosity of sediments is modified, i.e., either reduced or increased during diagenesis. In clastic sediments two main processes, which cause reduction in porosity, are cementation and compaction. Porosity of the sandstones is studied in terms of existing optical porosity (EOP) and minus cement porosity (MCP). Heald (1956) defined minus cement porosity as the porosity, which would be present if a specimen contained no chemical cement, i.e., the porosity that existed before cementation. If minus cement porosity of sandstone is almost equal to the original porosity of a freshly deposited sand, it would mean that the sandstone has suffered very little compaction before cementation. There have been several studies on random packing arrangements in sediments and in aggregates of spheres, which provide some information on initial porosities. Beard and Weyl (1973) showed that well sorted and artificially packed sands have porosities of about 39 percent, while Pryor (1973) studied recent sand bodies and obtained an initial porosity of about 45 percent. The depositional porosity for deltaic sands ranges between 42 to 50 percent (Atkin and McBride, 1992).

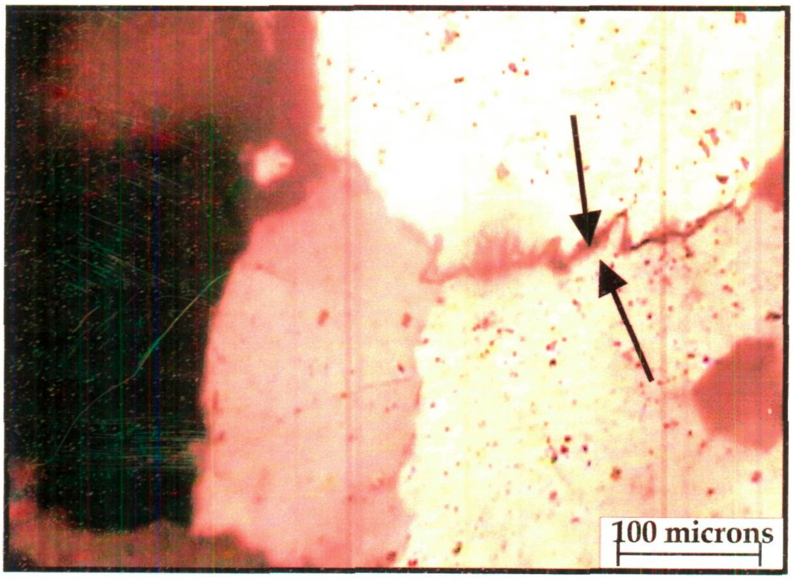
PLATE VII



A



B



C

PLATE VII

A. Photomicrograph showing point and long contacts.

B. Photomicrograph showing concavo-convex contact.

C. Photomicrograph showing sutured contact.

They took empirical porosity value equal to 45 percent and with this value they tried to model the porosity evolution and relative role of compaction and cementation. Considering the above described relationship, minus cement porosities of the studied sandstones were computed by adding the volume of cement to the volume of voids present. The volume of cement and voids were measured in each thin section.

Percentage of existing optical porosity (EOP) in the Upper Bhander Sandstone ranges from 1% to 12%, average 4% while minus cement porosity (MCP) ranges from 9% to 24%, average 18% (Table 14). Existing optical porosity develops due to dissolution of iron cement and feldspar grains. The first phase of diagenetic scenario in which the primary porosity is reduced by compaction and cementation processes is followed by later phase of partial dissolution of rock components resulting in the generation of secondary porosity of the rock. The common constituents that undergo dissolution include iron cement, feldspar and rock fragments. The important dissolution phase is relatively deeper subsurface feature. Most of the deep reservoir properties modify to a great extent to the dissolution process and result in secondary porosity. All the above mentioned observations made in the Upper Bhander Sandstone suggest that mechanical compaction, which started at sediment-water interface in early diagenetic environment progressively continued and resulted in chemical compaction in deep burial diagenetic environment. This type of diagenetic environments is characteristic of rapidly subsiding basins and consequent uplifting of the peripheral basin margin.

Table 14. Cementation and Porosity data for the Upper Bhander Sandstone in parts of Uttar Pradesh - Rajasthan States.
Fe= Iron oxide cement, Si= Silica cement, M = Matrix, EOP= Existing optical porosity, MCP= Minus cement porosity.

Sample No.	Detrital grains (%)	Cements and Matrix			Porosity	
		Fe	Si	M	EOP	MCP
Rasulpur Section						
R1	85	-	6	5	4	15
R2	87	-	6	3	4	13
R3	85	4	5	2	4	15
R4	78	4	9	4	5	22
R5	83	5	5	3	4	17
R6	87	-	6	3	4	13
R7	86	-	9	3	2	14
R8	90	-	5	4	1	10
R9	87	3	5	2	3	13
R10	80	1	9	4	4	18
R11	77	2	12	4	5	23
R12	82	2	6	5	5	18
R13	81	3	8	4	4	19
Tehra Section						
T1	79	5	9	2	5	21
T3	79	6	7	4	4	21
T5	83	-	13	-	4	17
T6	81	7	8	-	4	19
T7	80	1	18	-	1	20
T8	79	10	4	3	4	21
T9	87	7	1	2	3	13
T10	83	4	4	4	5	17
T11	80	6	8	1	5	20
T12	80	8	6	2	4	20
T13	84	6	2	2	6	16
T14	83	6	6	1	4	17
Bakoli Section						
B1	78	8	6	2	6	22
B2	77	7	8	4	4	23
B3	79	3	9	3	4	19
B4	85	2	9	1	3	15
B5	79	7	8	2	4	21
Rupbas Section						
RP1	80	5	6	6	3	20
RP2	79	5	4	4	4	17
RP3	85	8	1	2	4	15
RP4	77	10	1	6	3	20
RP5	82	9	1	3	5	18
RP6	83	4	6	4	3	17
Gatouli Section						
GH1	85	2	5	4	4	15
GH2	84	5	4	2	5	16

GH3	84	10	-	1	5	16
GH4	85	8	3	1	3	15
GH5	90	4	2	-	4	10
GH6	91	1	3	2	3	9
Mewali Section						
M1	78	11	3	4	4	22
M2	79	9	5	4	3	21
M3	85	6	3	5	1	15
M4	84	8	2	5	1	16
M5	84	9	1	4	2	16
M6	83	4	5	5	3	17
M7	80	10	4	4	2	20
Jagnair Section						
J1	85	3	7	3	2	15
J2	78	12	7	2	1	22
J3	86	4	4	4	2	14
J4	83	5	7	4	1	17
J5	78	12	7	2	1	22
J6	86	4	4	4	2	14
Holipura Section						
HP1	84	7	1	3	5	16
HP2	82	5	4	5	4	18
HP3	83	6	3	3	5	17
Tantpur Section						
TT1	83	5	4	4	4	17
TT2	78	6	7	5	4	22
TT3	77	16	2	1	4	23
TT4	82	10	2	2	4	18
TT5	78	12	2	4	4	22
TT6	77	14	2	4	3	23
TT7	76	13	4	4	3	24
TT8	77	12	5	3	3	23
Baretha Section						
BD1	80	7	5	4	4	20
BD2	89	3	4	2	2	11
BD3	82	3	5	7	3	18
BD4	80	3	10	4	3	20
BD5	85	-	8	3	4	15
BD6	89	-	6	2	3	11
BD7	89	2	4	2	3	11
BD8	80	5	5	5	5	20
BD9	81	7	5	4	3	19
BD10	76	5	10	5	4	24
BD11	80	4	12	2	2	20
Gchadi Bajana Section						
G1	82	8	5	2	3	18
G2	79	5	8	4	4	21
G3	78	7	8	4	3	22
G4	86	2	8	2	2	14
G5	85	2	6	3	4	15
Bansi Paharpur Section						
BP1	84	4	3	5	4	16
BP2	79	4	9	4	4	21
BP3	79	3	10	3	5	21
BP4	79	7	8	3	3	21

BP5	79	3	12	3	3	21
BP6	86	2	4	5	3	14
BP7	86	3	2	4	5	14
BP8	89	3	1	5	2	11
BP9	78	10	3	4	5	22
BP10	78	10	4	3	5	22
BP11	83	8	1	3	5	17
BP12	79	11	5	2	3	21
BP13	80	12	4	2	2	20
Rudawal Section						
RD1	82	1	13	-	4	18
RD2	83	2	9	4	2	17
RD3	80	-	15	3	2	20
RD4	79	-	18	-	3	21
RD5	90	-	10	-	-	10
RD6	80	3	14	-	3	20
RD7	78	-	18	1	3	22
RD8	79	6	12	-	3	21
RD9	79	2	16	-	3	21
RD10	83	-	12	2	3	17
Average Area Level	82	5	5	4	4	18

CEMENT

Two types of cementing materials occur in the sandstones of the study area viz silica and iron oxide. Clayey to silty matrix is also found occasionally which may be quashed / crushed pelitic rock fragments (Table 14).

Silica cement

The percentage of silica cement in the sandstones generally ranges from 1% to 18%, averages 5% (Table 14). In most of the samples silica cement occurs in the form of quartz overgrowth which shows the optical continuity with detrital quartz grains. Authigenic quartz overgrowths on detrital grains of quartz are observed to fill up the intergranular spaces partly. In some thin sections silica cement consists of mainly chalcedonic and microcrystalline quartz and some protochalcedonic quartz and mega-quartz. The chalcedonic quartz cement comprises radiating micro fibrous quartz forming fan-shaped aggregates. Microcrystalline quartz consists of subequant, randomly oriented interlocking grains of less than 0.06mm size and show pinpoint birefringence. Protochalcedonic quartz represents the incipient stage of silicification and occurs adjacent to the grain boundaries. Mega-quartz occurs as aggregate of drusy quartz showing straight extinction and normal refractive index.

Silica cementation is analyzed in detail observing nature of quartz grains (monocrystalline to polycrystalline), size, roundness, grain-grain contact, overgrowth-grain contact, overgrowth-overgrowth contact and development of silica overgrowth around the detrital grains. The quartz grains are mostly monocrystalline undulose followed by monocrystalline nonundulose and polycrystalline quartz. In the studied sandstone quartz overgrowth are mainly developed on monocrystalline quartz when compared to polycrystalline quartz grains (Table 15). Amongst monocrystalline quartz the overgrowth is more common around undulose grains as compared to nonundulose grains.

The quartz overgrowths were classified as per the percentage of the grain boundary covered in the plane of thin section as follows:

Total boundary covered (100%)	very well developed overgrowth
> 75% boundary covered	well developed overgrowth
75-50% boundary covered	moderately developed overgrowth
50- 25% boundary covered	poorly developed overgrowth
<25% boundary covered	under developed overgrowth

Most of the grains show moderately developed overgrowth followed by well developed, very well developed and poorly developed overgrowths (Plate VIIIA, B, C, D). Some samples show very well developed overgrowths. In terms of size, the overgrowths are more common around coarse grains than medium to fine grains of monocrystalline quartz population. Polycrystalline quartz with coarse size has rather well developed overgrowth as compared to finer and medium grained varieties.

Table 15. Development of quartz overgrowth with relation to size, roundness and type of grain contacts for the Upper Bhander Sandstone in parts of Uttar Pradesh - Rajasthan States.
VW=Very well; W =Well; M= Moderately, P= Poorly, WR= Well rounded, R= Rounded, SR= Sub rounded, SA= Sub angular, A= Angular, C= Coarse, M= Medium, F= Fine, P= Point, L= Long, C= Concavo-convex, S= Sutured.

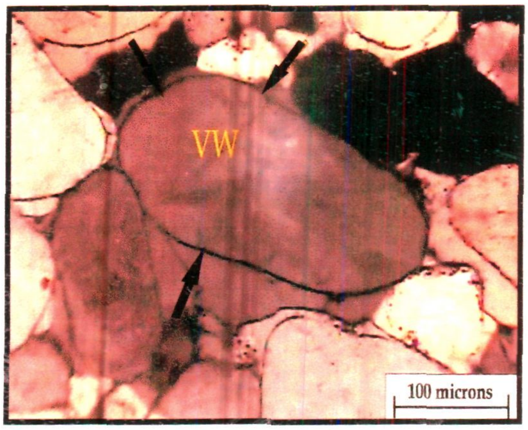
Sample No.	Types of quartz	Total %	Overgrowth Developed				Roundness					Size			Grain-grain contact				Overgrowth-grain contact				Overgrowth-overgrowth contact			
			VW	W	M	P	WR	R	SR	SA	A	C	M	F	P	L	C	S	P	L	C	S	P	L	C	S
Rasulpur Section																										
R1	Mono	100	-	30	45	25	-	12	67	21	-	-	85	15	28	68	-	4	33	65	2	1	18	77	3	2
R2	Mono	100	-	20	57	23	-	8	54	38	-	18	82	-	46	52		2	19	80	-	1	18	80	-	2
R3	Mono	100	3	27	59	11	37	47	5	11	-	63	37	-	27	72	-	1	18	80	-	2	58	42	-	-
R4	Mono	100	-	30	33	37	-	10	75	15	-	10	50	40	26	72	-	2	8	86	-	6	16	77	3	4
R5	Mono	100	-	20	33	47	-	11	55	34	-	25	75	-	32	66	-	2	67	28	-	5	13	87	-	-
R6	Mono	100	8	34	32	26	-	20	59	21	-	22	70	8	27	66	3	4	77	21	-	2	23	77	-	-
R7	Mono	100	7	40	33	20	-	25	61	14	-	55	40	5	31	65	-	4	26	71	2	1	11	84	2	3
R8	Mono	100	-	30	55	15	-	17	52	31	-	13	87	-	29	64	4	3	9	91	-	-	13	87	-	-
R9	Mono	100	-	20	56	24	-	8	54	38	-	18	82	-	26	73		1	20	80	-	-	18	80	-	2
R10	Mono	100	3	27	60	10	37	47	5	11	-	63	37	-	27	71	-	2	18	80	-	2	58	42	-	-
R11	Mono	100	-	30	33	37	-	10	75	15	-	10	50	40	22	77	-	1	38	61	-	1	16	79	2	3
R12	Mono	100	-	20	33	47	-	11	55	34	-	25	75	-	32	57	-	1	67	28	-	5	13	87	-	-
R13	Mono	100	8	34	32	26	-	20	59	21	-	22	70	8	37	61	-	2	88	11	-	1	23	77	-	-
Tehra Section																										
T1	Mono	100	3	40	23	34	5	24	61	10	-	22	78	-	30	65	3	2	12	88	-	-	17	78	2	3
T3	Mono	100	-	24	43	33	-	9	59	32	-	34	66	-	32	66	1	1	24	73	-	3	15	80	1	4
T5	Mono	100	-	37	23	40	-		55	45	-	24	64	12	21	72	2	4	20	76	-	4	15	83	1	1
T6	Mono	100	-	25	45	30	-	10	55	35	-	20	80	-	43	54	1	2	31	64	2	3	20	76	-	4
T7	Mono	100	-	36	56	8	-	10	70	20	-	23	77	-	39	59	1	1	30	68	-	2	13	87	-	-
T8	Mono	100	5	10	66	19	10	14	68	8	-	18	82	-	22	71	2	5	38	60	-	2	16	84	-	-
T9	Mono	100	-	20	47	33	-	19	56	25	-	20	70	10	38	59	-	3	21	79	-	-	19	69	1	2
T10	Mono	100	-	33	50	17	-	19	50	31	-	5	40	55	39	57	4	2	27	70	-	3	20	77	-	3

T11	Mono	100	8	11	61	20	13	25	44	18	-	21	79	-	32	65	2	1	24	72	-	4	53	47	-	-
T12	Mono	100	-	37	23	40	-		55	45	-	24	64	12	21	74	1	4	20	76	-	4	15	82	2	1
T13	Mono	100	-	25	45	30	-	10	55	35	-	20	80	-	34	60	4	2	32	65	1	2	20	78	-	2
T14	Mono	100	-	36	56	8	-	10	70	20	-	23	77	-	25	73	1	1	31	68	-	1	13	87	-	-
Bakoli Section																										
B1	Mono	100	-	30	45	25	-	12	67	21	-	-	85	15	28	69	-	3	33	65	-	2	18	77	3	2
B2	Mono	100	-	20	57	23	-	8	54	38	-	18	82	-	43	55		2	20	80	-	-	18	80	-	2
B3	Mono	100	3	27	60	10	37	47	5	11	-	63	37	-	27	71	-	2	24	74	-	2	58	42	-	-
B4	Mono	100	-	30	33	37	-	10	75	15	-	10	50	40	37	60	1	2	38	56	-	6	16	81	-	3
B5	Mono	100	-	20	33	47	-	11	55	34	-	25	75	-	32	65	-	3	67	27	-	7	13	87	-	-
Rupbas Section																										
RP1	Mono	100	-	23	60	17	-	17	67	16	-	33	67	-	28	68	-	4	16	80	-	4	33	67	-	-
RP2	Mono	100	-	12	65	23	-	33	57	10	-	23	62	15	46	53		1	30	67	-	3	44	56	-	-
RP3	Mono	100	-	33	54	13	-	20	55	25	-	20	80	-	27	71	-	2	20	79	-	1	40	60	-	-
RP4	Mono	100	-	20	55	25	-	19	45	36	-	20	80	-	26	72	-	2	31	69	-	-	80	18	-	2
RP5	Mono	100	5	10	55	30	-	26	66	8	-	23	77	-	32	55	-	3	30	70	-	-	12	88	-	-
RP6	Mono	100	-	15	55	30	-	36	46	18	-	12	88	-	27	66	3	4	39	61	-	-	23	77	-	-
Gatouli Section																										
GH1	Mono	100	-	23	63	14	-	12	77	11	-	23	60	17	23	72	1	4	11	88	-	1	10	88	-	2
GH2	Mono	100	5	10	55	30	-	26	66	8	-	23	77	-	40	58	-	2	30	70	-	-	12	88	-	-
GH3	Mono	100	-	15	55	30	-	36	45	19	-	12	88	-	39	59	1	1	39	61	-	-	23	77	-	-
GH4	Mono	100	-	20	47	33	-	19	60	21	-	20	70	10	22	71	2	5	21	79	-	-	28	69	1	2
GH5	Mono	100	-	33	50	17	-	19	50	31	-	5	40	55	35	62	-	3	28	66	-	6	20	77	-	3
GH6	Mono	100	8	11	61	20	13	25	43	19	-	21	79	-	33	60	4	3	24	72	-	4	53	47	-	-
Mewali Section																										
M1	Mono	100	-	23	60	17	-	17	66	17	-	33	67	-	26	71	-	3	18	80	-	2	33	67	-	-
M2	Mono	100	-	12	65	23	-	33	57	10	-	23	62	15	32	65	-	3	30	67	-	3	44	56	-	-
M3	Mono	100	-	33	54	13	-	20	55	25	-	20	80	-	27	68	1	4	20	79	-	1	40	60	-	-
M4	Mono	100	-	20	55	25	-	19	45	36	-	20	80	-	31	65	1	3	31	69	-	-	80	15	-	5
M5	Mono	100	-	23	63	14	-	12	77	11	-	23	60	17	29	67	1	3	11	88	-	1	10	88	-	2
M6	Mono	100	5	10	55	30	-	26	66	8	-	23	77	-	26	71		3	30	70	-	-	12	88	-	-
M7	Mono	100	-	15	55	30	-	36	45	19	-	12	88	-	27	71	-	2	39	61	-	-	23	77	-	-

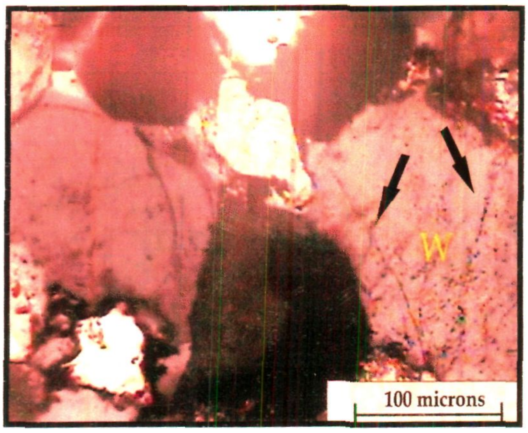
Jagnair Section																										
J1	Mono	100	-	23	60	17	-	17	67	16	-	33	67	-	19	76	1	4	16	80	-	4	33	67	-	-
J2	Mono	100	-	12	65	23	-	33	57	10	-	23	62	15	40	57	1	2	30	67	-	3	44	56	-	-
J3	Mono	100	-	33	54	13	-	20	55	25	-	20	80	-	39	59	1	1	20	79	-	1	40	60	-	-
J4	Mono	100	-	20	55	25	-	19	45	36	-	20	80	-	22	75	1	2	31	69	-	-	80	15	-	5
J5	Mono	100	-	5	65	30	-	23	67	10	-	15	75	10	35	62	-	3	21	79	-	-	30	68	-	2
J6	Mono	100	-	10	55	35	-	16	64	20	-	33	67	-	35	60	2	3	33	61	-	6	22	78	-	1
Holipura Section																										
HP1	Mono	100	-	23	63	14	-	12	77	11	-	23	60	17	36	61	1	2	11	88	-	1	10	88	-	2
HP2	Mono	100	5	10	55	30	-	26	66	8	-	23	77	-	29	67	1	3	30	70	-	-	12	88	-	-
HP3	Mono	100	-	15	55	30	-	36	46	18	-	12	88	-	26	72	1	1	39	61	-	-	23	77	-	-
Tantpur Section																										
TT1	Mono	100	-	20	47	33	-	19	56	25	-	20	70	10	32	66	1	1	21	79	-	-	19	69	1	2
TT2	Mono	100	-	33	50	17	-	19	50	31	-	5	40	55	19	76	1	4	27	66	-	7	20	78	-	2
TT3	Mono	100	8	11	60	21	13	25	44	18	-	21	79	-	40	57	1	2	24	72	-	4	53	47	-	-
TT4	Mono	100	5	10	55	30	-	26	66	8	-	23	77	-	30	68	1	1	30	70	-	-	12	88	-	-
TT5	Mono	100	-	15	55	30	-	36	46	18	-	12	88	-	22	74	2	2	39	61	-	-	23	77	-	-
TT6	Mono	100	-	33	54	13	-	20	55	25	-	20	80	-	35	62	-	3	20	79	-	1	40	60	-	-
TT7	Mono	100	-	20	55	25	-	19	45	36	-	20	80	-	33	64	1	2	31	69	-	-	80	18	-	2
TT8	Mono	100	-	5	65	30	-	23	67	10	-	15	75	10	32	65	2	1	21	79	-	-	30	67	-	3
Baretha Section																										
BD1	Mono	100	5	10	66	19	10	14	68	8	-	18	82	-	30	67	1	2	38	56	-	6	16	84	-	-
BD2	Mono	100	-	20	47	33	-	19	60	21	-	20	70	10	32	65	2	1	21	79	-	-	27	69	2	3
BD3	Mono	100	-	33	50	17	-	19	50	31	-	5	40	55	19	75	2	4	30	68	-	2	27	73	-	-
BD4	Mono	100	-	20	55	25	-	19	45	36	-	20	80	-	40	57	1	2	31	69	-	-	80	15	-	5
BD5	Mono	100	-	23	63	14	-	12	77	11	-	23	60	17	30	68	1	1	21	77	-	2	10	88	-	2
BD6	Mono	100	-	23	60	17	-	17	66	17	-	33	67	-	22	74	1	3	18	80	-	2	33	67	-	-
BD7	Mono	100	-	12	65	23	-	33	57	10	-	23	62	15	35	62	1	2	30	67	-	3	44	56	-	-
BD8	Mono	100	-	33	54	13	-	20	55	25	-	20	80	-	33	63	1	3	20	79	-	1	40	60	-	-
BD9	Mono	100	-	20	55	25	-	19	45	36	-	20	80	-	32	65	2	1	31	69	-	-	80	15	-	5
BD10	Mono	100	-	5	65	30	-	23	67	10	-	15	75	10	21	77	1	1	21	79	-	-	30	67	-	3
BD11	Mono	100	-	10	55	35	-	16	64	20	-	33	67	-	34	63	1	2	23	71	-	6	22	78	-	1

Gchadi Bajana Section																										
G1	Mono	100	-	33	54	13	-	20	55	25	-	20	80	-	19	76	1	4	20	79	-	1	40	60	-	-
G2	Mono	100	-	20	55	25	-	19	45	36	-	20	80	-	40	56	2	2	31	69	-	-	80	15	-	5
G3	Mono	100	-	5	65	30	-	23	67	10	-	15	75	10	30	68	1	1	21	79	-	-	30	66	1	3
G4	Mono	100	-	20	55	25	-	19	45	36	-	20	80	-	22	74	1	3	31	69	-	-	80	15	-	5
G5	Mono	100	-	23	63	14	-	12	77	11	-	23	60	17	37	59	1	3	21	77	-	2	10	88	-	2
Bansi Paharpur Section																										
BP1	Mono	100	-	23	60	17	-	17	67	16	-	33	67	-	30	68	1	1	16	80	-	4	33	67	-	-
BP2	Mono	100	-	12	65	23	-	33	57	10	-	23	62	15	22	74	2	2	30	67	-	3	44	56	-	-
BP3	Mono	100	-	33	54	13	-	20	55	25	-	20	80	-	35	63	-	2	20	79	-	1	40	60	-	-
BP4	Mono	100	-	20	55	25	-	19	45	36	-	20	80	-	33	63	2	2	31	69	-	-	80	15	-	5
BP5	Mono	100	-	5	65	30	-	23	67	10	-	15	75	-	32	65	2	1	21	79	-	-	30	63	-	7
BP6	Mono	100	-	10	55	35	-	16	64	20	-	33	67	-	21	76	1	2	33	61	-	6	22	78	-	1
BP7	Mono	100	-	20	55	25	-	19	45	36	-	20	80	-	19	76	1	4	31	69	-	-	80	15	-	5
BP8	Mono	100	-	23	63	14	-	12	77	11	-	23	60	17	40	57	1	2	11	87	-	2	10	88	-	2
BP9	Mono	100	-	20	57	23	-	8	54	38	-	18	82	-	30	68	1	1	20	80	-	-	18	80	-	2
BP10	Mono	100	3	27	60	10	37	47	5	11	-	63	37	-	22	74	2	2	18	81	-	1	58	42	-	-
BP11	Mono	100	-	30	33	37	-	10	75	15	-	10	50	40	35	63	-	2	38	59	-	3	22	77	-	1
BP12	Mono	100	-	20	33	47	-	11	55	34	-	25	75	-	22	74	2	2	31	62	-	7	13	87	-	-
BP13	Mono	100	8	34	32	26	-	20	59	21	-	22	70	8	35	63	-	2	11	88	-	1	23	77	-	-
Rudawal Section																										
RD1	Mono	100	-	20	57	23	-	8	54	38	-	18	82	-	32	66	1	1	20	80	-	-	18	80	-	2
RD2	Mono	100	3	27	60	10	37	47	5	11	-	63	37	-	19	76	1	4	18	80	-	2	58	42	-	-
RD3	Mono	100	-	30	33	37	-	10	75	15	-	10	50	40	40	56	2	2	38	56	-	6	21	77	-	2
RD4	Mono	100	-	20	33	47	-	11	55	34	-	25	75	-	30	68	1	1	67	32	-	1	13	87	-	-
RD5	Mono	100	8	34	32	26	-	20	59	21	-	22	70	8	22	74	1	3	77	21	-	2	23	77	-	-
RD6	Mono	100	-	20	55	25	-	19	45	36	-	20	80	-	35	59	2	4	31	69	-	-	80	15	-	5
RD7	Mono	100	-	23	63	14	-	12	77	11	-	23	60	17	33	63	1	3	11	87	-	2	11	88	-	1
RD8	Mono	100	-	33	54	13	-	20	55	25	-	20	80	-	32	65	2	1	20	79	-	1	40	60	-	-
RD9	Mono	100	-	20	55	25	-	19	45	36	-	20	80	-	32	66	1	1	31	69	-	-	80	15	-	5
RD10	Mono	100	-	5	65	30	-	23	67	10	-	15	75	10	19	75	2	4	21	79	-	-	30	68	-	2
Average Area Level			3	25	52	20	2	20	56	22	0	22	70	8	30	67	1	2	28	69	1	2	31	66	1	2

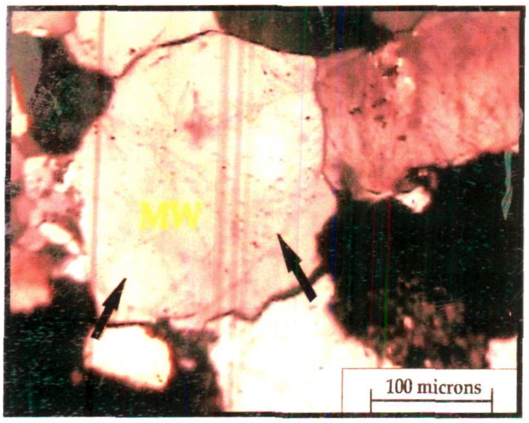
PLATE VIII



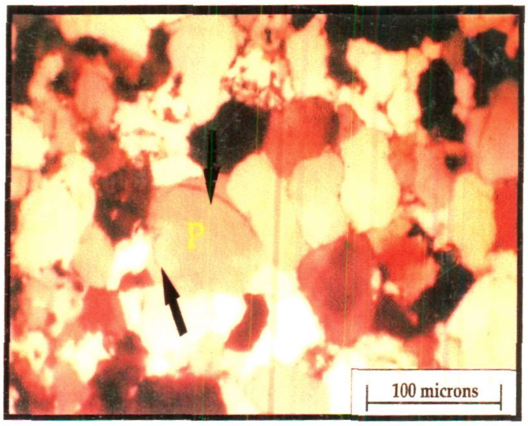
A



B



C



D

PLATE VIII

A. Photomicrograph showing very well developed overgrowth around detrital grains.

B. Photomicrograph showing well developed overgrowth around detrital grains.

C. Photomicrograph showing moderately well developed overgrowth around detrital grains.

D. Photomicrograph showing poorly developed overgrowth around detrital grains.

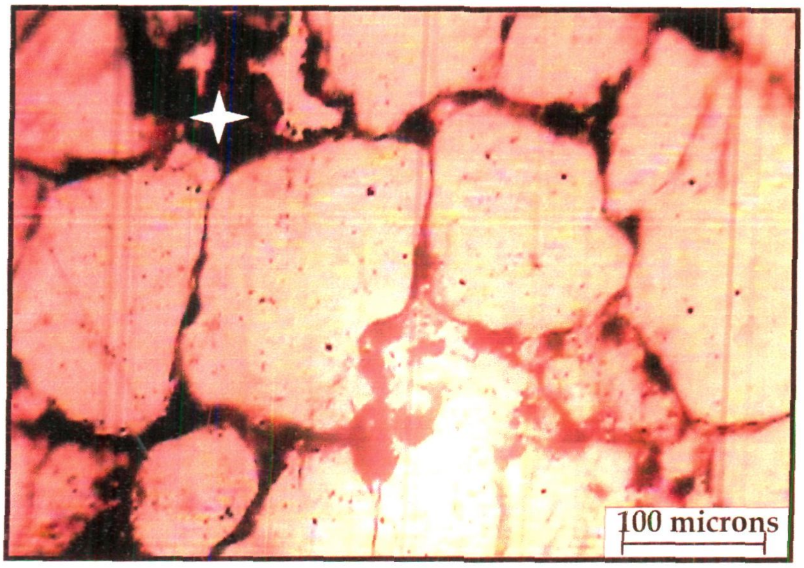
As per the Power (1953) roundness scale; the monocrystalline grains (undulose and nonundulose) are generally subangular to subrounded. The relationship between grain roundness and overgrowth indicates that the overgrowths are more

common on subrounded and rounded grains followed by subangular and angular (Table 15). The pressure solution of detrital quartz and other silicates at grain contacts are important source for silica in deeply buried sandstones. The possible source for cryptocrystalline quartz cement is intercalations of tuff and volcanic rock fragment which are characteristics of marine sedimentation in rift basin. Chalcedony also precipitates rapidly from concentrated solution of silica, whereas in the later stages mega quartz crystallizes slowly from dilute solutions (Versy, 1939).

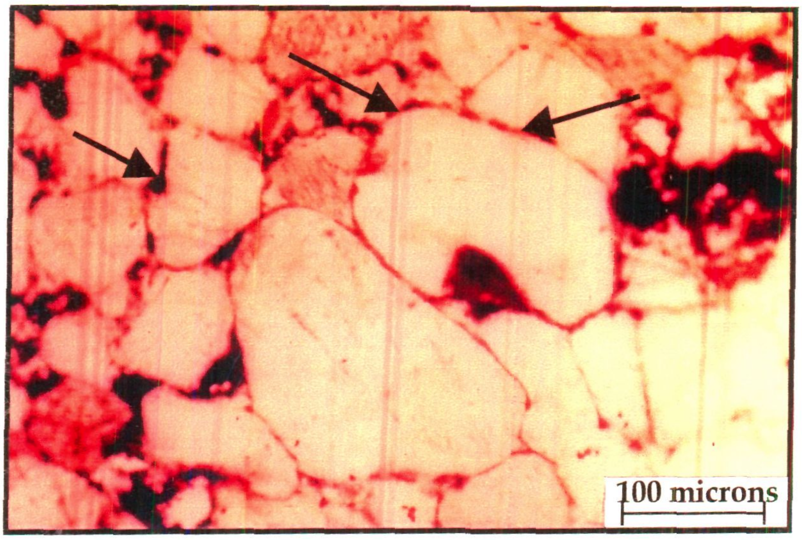
Iron Oxide Cement

Most of the studied samples show iron oxide cements which forms 1% to 14% and averages at 5%. Iron oxide cement occurs in the form of black coatings around detrital grains as well as patches. This coating is variable in thickness ranging from 10 to 26 microns. Similar coatings also occur around altered and leached feldspar grains. In these grains iron oxide also occurs along the cleavage traces. In some thin sections empty voids are lined with a thin coating of iron oxide. These voids represent completely leached feldspars which have disappeared leaving behind empty voids. The oversized pore spaces might have been resulted from destruction and leaching of labile framework grains, possibly feldspars (Plate IXA).

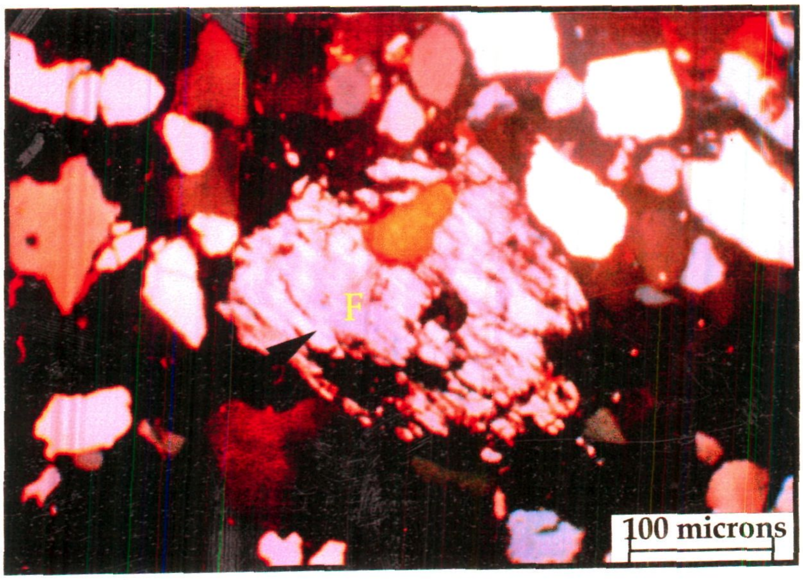
PLATE IX



A



B



C

PLATE IX

A. Photomicrograph showing oversized pore spaces (X).

B. Photomicrograph showing detrital quartz grain corroded by iron cement.

C. Photomicrograph showing feldspar grain corroded by iron cement.

In many instances, the clastic grains have lost their grain morphology and are present now in the form of protrusions, embayment and notches (Plate IXB, C). Iron oxide in sediments may have formed just after the deposition at the sediment -water interface but was regenerated during burial (Walker, 1974).

MATRIX

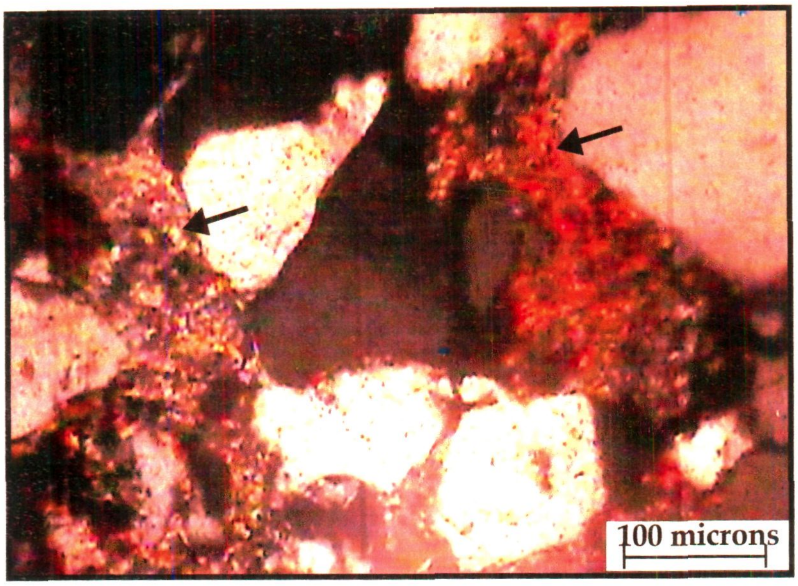
Clayey to silty matrix is present in varying amounts in the studied sandstones (Plate XA, B). The matrix compositionally represented by fine grained muscovite, clay and silt size quartz grains. Both syndepositional and post depositional matrix is present. The matrix, therefore, influence diagenetic processes through its chemical entities and bulk properties, such as porosity and permeability by the process of pore occlusion.

DIAGENETIC MODIFICATION

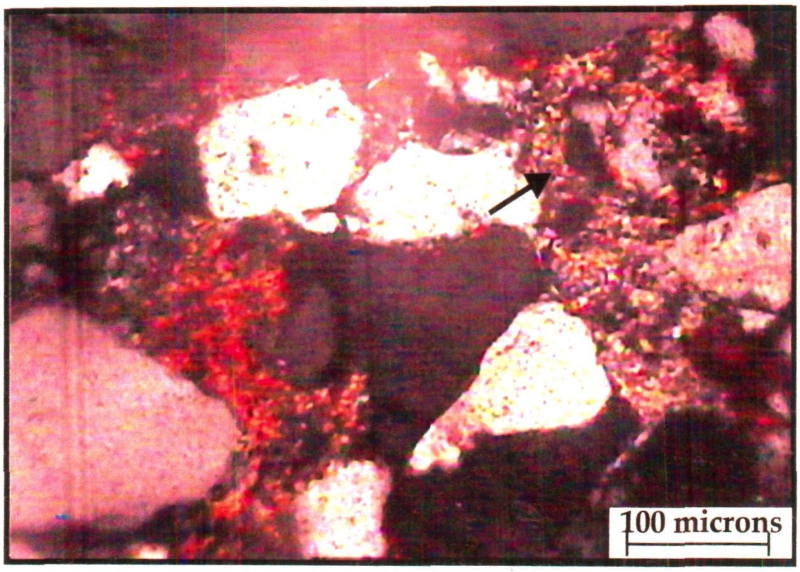
The post depositional alterations of detrital sediments by diagenetic processes are the important factors influencing the detrital mineralogy of the sandstones. Thus the effect of diagenesis must be taken into account at the time of provenance interpretation through detrital modes (McBride, 1985). Just after sediment deposition the diagenetic processes start to bring the equilibrium with the existing physico – chemical conditions. Diagenetic processes operating from the zone of weathering to the deep surface where it grades into metamorphism are responsible for producing hard compact rock from undulated soft sediments.

The major diagenetic effects are the loss of detrital grains by dissolution, the alteration of grains by replacement or recrystallization and loss of identity of

PLATE X



A



B

PLATE X

A, B. Photomicrograph showing detrital grains corroded by clayey to silty matrix.

certain ductile grains during compaction by production of pseudomatrix.The Upper Bhander Sandstones were studied with a view to interpret the diagenetic processes and their effects on the studied sandstones. The effects of compaction and dissolution can be inferred by types of grain contact, porosity reduction and oversized pore spaces.

During early stages of diagenesis, mechanical compaction was the dominant process. It caused rotation and adjustment of grains and formation of point and long contacts. Compaction, largely influenced by roundness of detrital particles was possible in the absence of an early major cementation phase that could have stabilized the detrital framework. The presence of highly weathered feldspar grains as well as oversize pore spaces in the studied sandstones indicates dissolution of detrital grains. About 1 percent existing optical porosity of the studied sandstones has resulted from dissolution of detrital grains mainly feldspars and iron cement. Dissolution and loss of feldspar can take place in the shallow weathering zone or in the deep surface (McBride, 1985). The shallow depth of burial and lack of illitization suggests that the feldspars in the studied sandstone were destroyed in the shallow weathering zone.

Generally original sandstone porosity is 45 percent which was reduced to an average of 18 percent. Three processes are commonly important in modifying intergranular porosity; mechanical compaction, chemical compaction and cementation. Houseknecht (1987) proposed a method to estimate quantitatively the porosity loss by compaction using modal analysis. Intergranular volume (Weller, 1958), which is synonymous with minus cement porosity, is the sum of intergranular porosity plus all cements that occupy the intergranular space. Intergranular volume is occluded and reduced by cementation and compaction during diagenesis. The studied sandstones are divided into two groups on the basis of diagenetic features i.e., one group that was subjected to more compaction then cementation and other group that was subjected to more cementation than compaction.

The process of replacement has not been very effective in modifying the detrital composition of the Upper Bhander Sandstone. The replacement of quartz grains by iron oxide and silica cements is only partial and localized and hence composition of the original grains is determinable. Among the various cements, quartz was the first to be precipitated in the form of overgrowths partially filling in the interparticle pore space. Silica cement in later part was partially replaced by iron oxide. The silica forming overgrowth was probably derived from dissolution of quartz grains and/or from compaction water. Iron oxide formed due to weathering and pedogenic processes.

SUMMARY AND CONCLUSION

The Vindhyan basin, situated in the central part of India is one of the largest Meso-Neoproterozoic basins of the Indian Peninsula. It extends over a strike length of more than 1, 62,000 km in NE-SW direction. The Vindhyan basin is bordered by the Aravalli-Delhi orogenic belt (2500-900Ma) (Roy, 1988) in the west, Son-Narmada lineament in the southwest and the Satpura orogenic belt (1600-850Ma) (Verma, 1991) in the southeast. The basin shows geometry of a half graben (Ram et al., 1996) and is deepest towards the southwest in the proximity of Son-Narmada lineament. It gradually shallows up to the northwest towards Bundelkhand Massif. The Upper Bhander Sandstone Formation which defines northerly extension of the great Vindhyan Basin is a fossil graben with over 4500m thick metasedimentary successions. The present investigation area spreads over 70 Square kilometers confining between latitude 26°50′ and 26°56′30″ north and longitude 77° 25′ and 77° 37′ east. The area lies in the south-west of Agra-Fatehpur Sikri tract and represents small part of the long belt of Upper Bhander Sandstone Formation which extends for about >100km up to Karauli. The infillings of the Upper Bhander Sandstones are composed of shale and thin bedded, fine to medium grained sandstone. The sandstone is hard and compact , dark red to brick red with white spots. Stratigraphically, the Vindhyan Supergroup is subdivided in two successions on the basis of their distinct tectonic settings. The Lower Vindhyan developed in an intracratonic rift basin (Bose et al., 1997) and the Upper Vindhyan formed in an intracratonic sag basin (Sarkar et al., 2002) with a compressional interlude in between. Each of this succession has been further sub-divided into formations and members in conformity with the 'code of stratigraphic nomenclature of India'.

In the present work, an attempt has been made to interpret various lithofacies belonging to the Upper Bhander Sandstone of the Vindhyan Basin with reference to depositional processes and sedimentary environments to adduce a depositional model as well as to envisage provenance, tectonic setting and diagenetic history using sandstone petrography and diagenetic aspects as tools.

The study area of Upper Bhander Sandstone of Vindhyan Supergroup rocks is constituted by a heterogeneous assemblage of sandstones and shale which occur as scattered outcrops. Generally the Upper Bhander Sandstones exhibit variable colors of pink, red, brownish yellow, yellow and white etc. Most of the sandstones are hard and compact, massive and occasionally friable. Their is vertical variations in the primary sedimentary structures. These structures include tabular and trough cross-bedding, herring-bone cross-bedding, ripple marks, channel sandstone body, laminations etc. In the present work, thirteen lithostratigraphic sections are described. These sections were measured, analyzed in the field and (200) representative sandstone samples were collected for their petrographic examination. Amongst which 105 samples were finally chosen for the study. The sandstone samples were cut into standard petrographic thin-sections. They were stained with cobaltinitrate for potassium feldspar recognition. 250 to 300 grains were counted per thin section. The traditional methods (Ingersoll et al., 1984) were used to classify and tabulation of grain types. Standard petrological techniques using a polarizing microscope were employed to describe the thin sections. Authigenic components (cement and matrix replacement constituents) were counted separately. The heavy mineral separation was done following Carver (1971), and identification was undertaken following Krumbein and Pettijohn (1938) as well as Milner (1962). Taylor (1950) method was applied for the study of the nature of detrital grain contacts and for computation of contact index; the method of Pettijohn et al., (1987) was used. The diagenetic process of sandstones was taken into account to check the modification of original detrital composition while attempting interpretation of provenance. Detrital mineralogy of the sandstones including lighter and heavy minerals were studied for the purpose of petrographic classification of the sandstones and interpretation of their provenance. Classification scheme of Folk (1980) based on composition of detrital constituents and Dickinson (1985) scheme based on the tectonic setting of the provenance were used.

Nine lithofacies are defined on the bases of lithology, sedimentary structures, geometry and palaeocurrent directions. The lithofacies are named and coded individually following Miall's (1977) scheme. These are tabular cross-bedded sandstone facies , trough cross-bedded sandstone facies , massive sandstone facies , interbedded shale and fine grained sandstone facies , parallel laminated sandstone facies , ripple laminated sandstone facies , shale facies , channel sandstone facies , and herringbone cross-bedded sandstone facies.

The statistical parameters of grain size analysis show that the sandstones are medium to fine grained, moderately to moderately well sorted, strongly fine skewed and mesokurtic to leptokurtic. Most of the grains are subangular to subrounded and have low sphericity. Bivariant plots of various parameters show no systematic relationship between mean size versus sorting, mean size versus roundness, mean size versus sphericity, roundness versus sorting and sphericity versus sorting. Overall textural maturity of the Upper Bhander Sandstone can be considered as mature to supermature. The studied sandstones show bimodality in term of coarser and finer layers.

The depositional processes and environment have been employed to categorize three main genetic lithofacies assemblages. Facies association I (FAI) is constituted of lithofacies like tabular/trough cross-bedded sandstones, herring-bone cross-bedded sandstones, wave ripple-bedded sandstone, parallel laminated sandstone along with interbedded shaly-thinly bedded fine grained sandstone and represents prograding high energy estuarine deposits. Facies association II (FAII) consists of a tabular package of tabular cross-bedded sandstones, trough cross-bedded sandstones, parallel laminated sandstone, massive sandstone and channel sandstone body and it represents tidal and ebb channel deposits. Facies association III (FAIII) represents foreshore-offshore deposits and is characterized by the presence of five lithofacies; large scale tabular cross-bedded sandstones, symmetrical and asymmetrical ripple, interference ripples and laminated sandstone. These contrasting palaeoenvironmental settings suggest deposition at the basin margin, through several episodes of transgression and consecutive regression, evidence of which are well-documented in the study area. The polymodal to bimodal-bipolar pattern of tabular and trough cross-beds, lower value of vector magnitude (47%) and higher values of variance (7548) indicate large azimuthal dispersion perhaps due to diverse current system of coastal environment including tidal and longshore currents. The diagonally /opposite oriented modal classes of the two types of cross beddings at various sections of the study area are genetically significant and may correspond to ebb tidal/foreshore currents directed towards east or southeast and backshore/flood tidal currents parallel to or across the shoreline towards west or northwest.

According to Folk (1980) classification, the Upper Bhander Sandstone are mainly quartzarenite. The framework grains are mainly quartz followed by feldspar, rock fragments, micas and heavy minerals. Most of the quartz grains are monocrystalline, rest being polycrystalline. The monocrystalline quartz generally shows undulatory extinction. Polycrystalline quartz grains possess both sharp and sutured intercrystalline boundaries. Feldspars include plagioclase and microcline, both fresh and altered varieties. Biotite as well as large flakes of muscovite mica are observed. Rock fragments include chert, shale, schist, phyllite etc. Average detrital mineralogy includes monocrystalline quartz (90.98 %), polycrystalline recrystallised metamorphic quartz (1.82 %), stretched metamorphic quartz (1.76 %), feldspar (2.10 %), rock fragments (2.42 %), mica and heavy minerals (0.92%). The detrital grains of the Upper Bhander Sandstone are in the sand size range. Due to presence of small amount of feldspar and rock fragments in the studied sandstone, prolonged reworking and presence of high gradient stream is quite likely within the basin.

Occurrence of zircon, tourmaline, and rutile suggest an origin from igneous (plutonic) source rocks. Presence of epidote, garnet and staurolite indicate a source of metamorphic rocks (Wanas et al. 2006). Thus the suite of heavy minerals suggests various sources probably Precambrian metasediments, Bundelkhand massifs and granite- gneiss of Aravalli –Delhi Supergroup. These probable sources contributed the sediments to the basin from SW, NE and NW direction of the study area. The data on the types of quartz in diamond diagram yields consistent result that indicates a source area containing largely of plutonic and upper metamorphic rocks, which represent the exposed roots of magmatic cores or older crystalline basement in the area (Dickinson and Suczek, 1979).

To understand the tectonic settings of the Upper Bhander Sandstone, all the petrofacies were plotted in the Qt-F-L, Qm-F-Lt, Qp-Lv-Ls, Qm-P-K standard diagram, given by Dickinson (1985). The Qt-F-L diagram which emphasizes factors controlled by provenance, relief, weathering and transport mechanism is based on total quartzose, feldspars and lithic content. Most of the samples lie in continental block provenance field suggesting contribution from the craton interior with basement uplift. Rest of the samples fall in the recycled orogen provenance which suggest their derivation from metasedimentary and sedimentary rocks that were originally deposited along former passive continental margins (Dickinson, 1985). The Qm-F-Lt plot showed that the samples fall in continental block provenance with little contribution from the recycled orogen provenance. In the Qm-P-K diagram, the data lie in the continental block provenance reflecting maturity of sediments and stability of source area. In Qp-Lv-Ls plot, the sample data mostly fall in the intracratonic rift basin. Analysis of data from the plotting of triangular diagram doesn't exactly suggest the same interpretation which is due to the weathering and post-diagenetic modification of the unstable minerals. Considering the analysis of data plotted on different triangular diagram, a tectonic collage can be suggested as tectonic setting. This interpretation is also supported by the evolutionary history of the Vindhyan Basin. The tectonic setting of the Vindhyan basin is seemingly akin to that of the Indus Ganga and Alpine basins, both located on subducting plate and cited as example of peripheral foreland (Dickinson,1974; Reading,1986), foredeep (Miall,1984,2000) basin. The sedimentary fill and stable setting of the Vindhyan Basin are 'however', unlike those of the aforesaid foreland basins overlooking the rising fold belts of high relief, in which thick terrigenous sediments mainly comprising polymictic coarse clastics are deposited at a rapid rate. Moreover, paucity of coarse and polymict clasts and dominance of quartzarenite and good textural maturity in the basal part of Vindhyan Supergroup (i.e., Semri Group) suggest that the highlands providing the sediment debris to the peripheral basin were reduced to low relief due to protracted erosion of the uplifted fold belt. This discrepancy in the post orogenic Vindhyan basin is inexplicable, pending relevant data in respect of the original deposition and abundance of sandstone and conglomerate facies and basement deepening (flexuring) in the basal/ proximal parts. Dominance of quartzarenite and good textural maturity in the Upper Bhander Sandstone suggest that the highlands formed by upliftment fold belts provided sediment debris to low relief area through their protracted erosion.

The studied sandstones are divided into two groups on the basis of diagenetic features i.e., one group that was subjected to more compaction than cementation and other group that was subjected to more cementation than compaction. The sandstones consist of silty and clayey matrix. The matrix compositionally represents fine-grained monocrystalline quartz, muscovite and feldspar grains. The framework constituents of the Upper Bhander Sandstone exhibit mainly long contacts (50%) followed by point contacts, which explains the high value of average contact index in the studied samples. Porosity of the sandstones is studied in terms of existing optical porosity (EOP) and minus cement porosity (MCP). Average percentage of EOP is 4 and average MCP percentage is 18. The primary porosity of the rock is reduced by compaction and cementation through mechanical processes in the early stage of diagenesis, and through chemical processes in the later stage, which finally results in the generation of secondary porosity. Compaction, largely influenced by roundness of detrital particles was possible in the absence of an early major cementation phase that could have stabilized the detrital framework. Major diagenetic event was alteration and dissolution of feldspars. The feldspar grains show different stages of alteration. At places, complete dissolution of feldspar grains resulted in oversize pores. Dissolution and loss of feldspar can take place in the shallow weathering zone or in the deep surface (McBride, 1985). The shallow depth of burial and lack of illitization suggest that the feldspar in the studied sandstones were destroyed in the shallow weathering zone.

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